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LIMNOLOGY OF YELLOWTAIL RESERVIOR AND THE BIGHORN RIVER

Montana State University
Bozeman, Montana

February 1973

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Limnology of Yellowtail Reservoir and The Bighorn River

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27 Abstract

Impoundment and deep water withdrawal displaced the maximum and minimum temperatures and conductivities of the effluent two to four months behind the influent occurrence and greatly reduced the amplitude of seasonal change. Of the influent total carbon, nitrogen and phosphate, 24%, 25% and 86% respectively were retained in the reservoir. The major fraction retained was the particulate portion. A significant correlation was found between total phosphate, orthophosphate and turbidity. Nitrate, ortho-phosphate and trace metals were in higher concentration in the upper end of the reservoir associated with turbid water. A withdrawal caused density current was evident which altered the vertical and longitudinal distribution of physical and chemical parameters. Volume based phytoplankton density and chlorophyll concentration decreased down-reservoir. However, the depth of the euphotic zone increased down-reservoir as silt settled out. Consequently the euphotic zone standing crops were greatest in the mid-section of the reservoir. Insufficient light penetration was the principal limiting factor to primary production in the upper end of the reservoir. Decreased primary productivity in the lower end of the reservoir did not appear to be due to nutrient limitation. (EPA)

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LIMNOLOGY OF YELLOWTAIL RESERVOIR AND THE BIGHORN RIVER

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ABSTRACT

Chemically, water impounded in the reservoir, was a calcium, sodium, sulfate, bicarbonate type. Mean salinity of the effluent was essentially the same as that of the influents. There was a striking increase in water clarity down the reservoir due to settling of silt.

Impoundment and deep water withdrawal displaced the maximum and minimum temperatures and conductivities of the effluent approximately two months behind the influent occurrance and greatly reduced the amplitude of seasonal change.

Of the influent total carbon, nitrogen and phosphate, 24%, 25% and 86% respectively were retained in the reservoir. The major fraction retained was the particulate fraction. Of the trace metals there was a 97% retention for iron, 86% for manganese, 40% for copper and 71% for zinc. Particulate carbon, nitrogen, and phosphate, orthophosphate, nitrate and trace metals were in higher concentration in the upper end of the reservoir associated with silt.

A withdrawal created density current was evident which altered the vertical and longitudinal distribution of physical and chemical parameters.

Volume based phytoplankton density and chlorophyll concentration decreased down-reservoir. However, the depth of the euphotic zone increased down-reservoir as silt settled out. Consequently the euphotic zone standing crops were greatest in the mid-section of the reservoir. Insufficient light penetration was the principal limiting factor to primary production in the upper end of the reservoir. Decreased primary production in the lower end of the reservoir did not appear to be due to nutrient limitation.

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SUMMARY AND CONCLUSIONS

1. Bighorn Lake, an impoundment of the Bighorn River, has a maximum useable capacity of 169 x 19^7 m^3 (1,375,000 acre-ft) and a surface area of 700 x 10^5 m^2 (17,298 acres). The principal purposes of the reservoir are flood control, power production, irrigation and recreation.

2. The reservoir became thermally stratified for all three years of the study. Surface water temperatures were greater than 20 C in late July and August. Bighorn Lake acquired an ice cover for a period of approximately 60 days in 1969. The spring warming process began in the upper end of the reservoir and advanced toward the dam and to greater depths as the season progressed. The development of a distinct thermocline for any given year of the study was not detectable.

3. Conductivity ranged from 430 to 1,628 micromhos. Differences in conductivity by season and location are depicted for the 1968 sampling periods. Reservoir regulation delayed normal trends in conductivity. Water of minimal conductance (salinity) was discharged from the dam between July and September, which corresponds to the periods of heavy downstream irrigation.

4. Calcium, sodium, sulfate and bicarbonate are the most common constituents of the dissolved solids present in Bighorn Lake. Photosynthetic reduction of alkalinity was not detected.

5. Turbidities were drastically reduced thus improving water quality. A comparison of the mean turbidities for the Bighorn and Shoshone Rivers with that of the reservoir discharge during the study reveals approximately a 60-fold decrease. A turbidity current was established at the depth of the power penstock during 1968. Nitrate nitrogen and orthophosphate maxima as well as the oxygen and pH minima were associated with the above turbidity current.

6. It was apparent that Bighorn Lake was fertilized with nutrients from the major tributaries. The relationships of conductivity, turbidity, nitrogen and phosphate to the rate of tributary flow have been examined. It does not appear that any of the determined essential ions for biological production are lacking in this reservoir.

7. Maximum phytoplankton volumes were found in the spring and early summer months. A definite algal succession pattern was established for all three years. Phytoplankton volumes increased from the dam to the upper end of Bighorn Lake.

8. Comparison of sampling periods (June-September) common to all years of the study showed that the calculated net primary production increased 84% in 1970 over 1968. The above increase in productivity related well with the 44% increase of mean total phytoplankton standing crop (mm^3/m^2) in 1970 over 1968 as well as the 49% increase in mean chlorophyll *a* concentrations (mg/m^2) in 1970 and 33% increase in mean phytoplankton biomass (g/m^2).

INTRODUCTION

The decline in "productivity" of newly impounded reservoirs is almost universal (Bennett, 1971; Carlander et al., 1963; Neel, 1963). Productivity in this context refers to the successful establishment and maintenance of a large population of preferred fishes. The initial high productivity has been attributed to the organic matter and nutrients resulting from the flooded soil and vegetation, thus entering the trophic cycle of the reservoir. Although the above enrichment process may have some validity in humid regions it is rather doubtful if this is applicable to semi-arid regions.

Whether or not this loss of fish production is related to a decline in primary or secondary productivity, or both has not been established.

A comprehensive investigation of the physical, chemical and biological limnology of Bighorn Lake (formerly Yellowtail Reservoir) and its tributaries was initiated in the fall of 1967 to determine if a decline in primary productivity of this new impoundment would occur. The study specifically encompassed the heat budget, salinity regime, internal currents and biological productivity (phytoplankton) of the reservoir.

The three-year study was undertaken to relate the physical and chemical environment of the reservoir to primary production and to determine what changes in the primary production took place over the entire study. An effort was also made to assess the physical and chemical characteristics of the influent and effluent waters of the reservoir.

The theoretical points of the above approach to primary production are best summarized by Findenegg (1965) as follows:

> "It is a well known fact that primary production in lakes is controlled by the interaction of many factors which usually are divided into three groups: (1) Physical factors originating directly or indirectly from solar radiation, such as light conditions, temperature, mixing and turbulence by the action of the wind; (2) The content of the nutrients in the euphotic zone of the lakes, and (3) The interaction of the organisms present in the plankton community which may promote or hamper the production of certain species".

The cause(s) of the decline in reservoir fish production must be known before formulation of better and more feasible fisheries management (both preventive and corrective) can be applied.

DESCRIPTION OF THE STUDY AREA

Bighorn Lake is a new impoundment (Yellowtail Dam) of the Bighorn River approximately 80.5 kilometers (50 miles) southeast of Billings, Montana, Yellowtail Dam is in Bighorn County at lat. 45°18'27", long. 107°57'26", in SW1/4 SE1/4 Sec. 18, T.6 S. and R. 31 E. At normal operating level the reservoir extends from the dam at Fort Smith, Montana into Wyoming for a distance of 98.4 kilometers (61 miles). The water is used for power production, flood control, irrigation and recreation.

Construction of the dam by the Bureau of Reclamation began in 1961 and was completed in 1967. Storage began 4 November 1965. The reservoir has a usable capacity (Fig. 1) of 169 x $10^7 m^3$ (1,375,000 acre-ft) below elevation 1,114.6 m (3,657 ft). Normal operating capacity is 144 x $10^7 m^3$ (1,097,000 acre-ft) at elevation 1,109.5 m (3,640 ft) and minimum operating level is 60 x $10^7 m^3$ (483,400 acre-ft) at elevation 1,081.1 m (3,547 ft). Dead storage amounts to 234 x $10^5 m^3$ (18,970 acre-ft) below elevation 1,005.8 m (3,296 ft). Maximum daily content since construction occurred on 6 July 1967 with 166 x $10^7 m^3$ (1,346,000 acre-ft) at elevation 1,114.5 m (3,656 ft), while the minimum since first filling occurred on 22 May 1968 and was 82 x $10^7 m^3$ (667,400 acre-ft) at elevation 1,093.0 m (3,586 ft). Other morphometric data for the reservoir are given in Table I.

Details of the structure of the thin concrete-arch dam are shown in Figure 2. Water can be discharged from the reservoir through three outlets; (1) the spillway--elevation 1,095.1 m (3,593 ft); (2) the power penstocks--elevation 1,051.6 m (3,450 ft), and (3) the river outlet invert-- elevation 1,005.8 m (3,296 ft). Unless it is necessary to discharge water through the spillway or river outlet invert, all water is discharged from the reservoir through the power penstocks. The depth of water overlying the power penstocks would be 63.1 m (207 ft) at maximum usable capacity, 57.9 m (190 ft) at normal operating level and 29.6 m (97 ft) at minimum operating level. Discharge through the river outlet invert would come from very deep water; 109.9 m (360 ft) at maximum usable capacity, 96.8 m (317 ft) at normal operating level and 76.4 m (250 ft) at minimum operating level.

Six permanent sampling stations were established on the reservoir during the course of the study (Fig. 3). Kilometer 0 (Station 0) was located at the dam site with the remaining stations at approximately 16.1 kilometer (10 mile) intervals from each other up the reservoir for 80.5 kilometers to station 5.

The major tributaries to the reservoir, as can be seen from Figure 3, are the Bighorn and Shoshone Rivers. The average discharge for the Bighorn River was 63.9 m^3/sec (2,256 cfs) for a 41 year period (U.S.G.S., 1969). The discharge normally fluctuates between a fall

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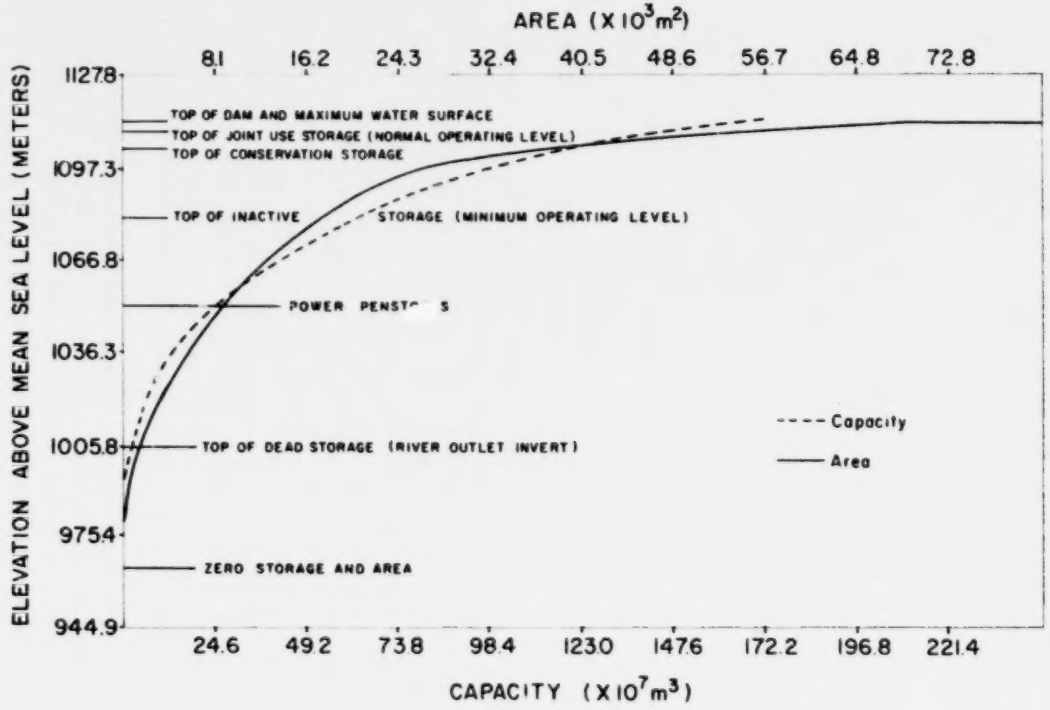

Figure 1. Water levels of Bighorn Lake as related to area ($X10^3$ m^2) and capacity ($X10^7$ m^3) with operational zones delineated (Bureau of Reclamation Data).

Table I. Additional morphometric data for Bighorn Lake at maximum capacity (elevation 1,115.5 m).

Maximum Length	98.4 km (61 mi)
Maximum Effective Length	9.8 km (6.1 mi)
Maximum Width	3.2 km (2.0 mi)
Maximum Effective Width	3.2 km (2.0 mi)
Mean Width	739 m (2,425 ft)
Maximum Depth	140 m (459 ft)
Mean Depth	24 m (80 ft)
Area	727×10^5 m^2 (17,958 acres)
Volume	176×10^7 m^3 (1,427,840 acre-ft)
Length of Shoreline	206 km (128 mi)
Shoreline Development	11.8
Slope of Basin	0.14%

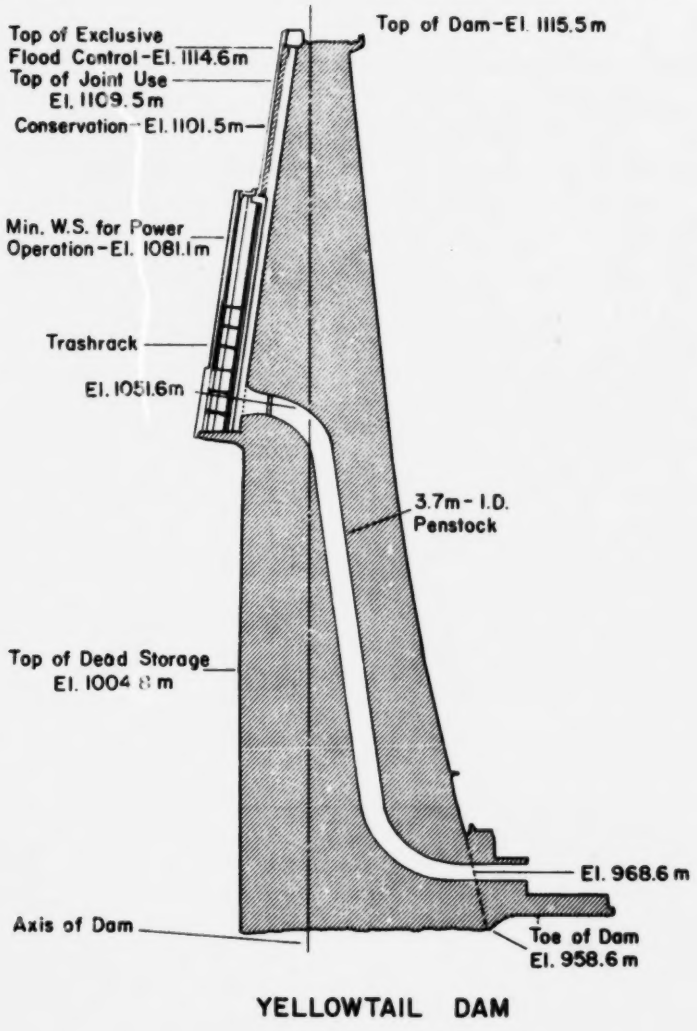

Figure 2. Detailed structure of Yellowtail Dam. Diagram was furnished through the courtesy of the Bureau of Reclamation.

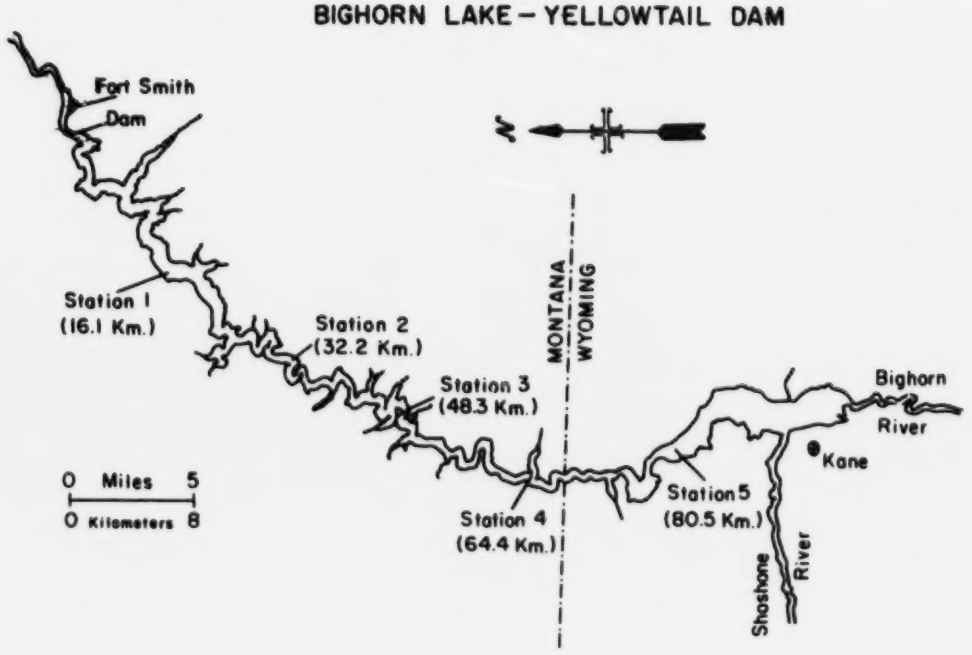

Figure 3. Map of Bighorn Lake (Bureau of Reclamation) showing location of the six permanent sampling stations.

minimum of approximately 21.2 m^3/sec (750 cfs) and a spring maximum of 339.8 m^3/sec (12,000 cfs). Maximum recorded discharge was 712.7 m^3/sec (25,000 cfs) on 16 June 1935 and the minimum was 5.1 m^3/sec (179 cfs) on 22 July 1934. The drainage area of this river comprises 40,831 km^2 (15,765 mi^2) at an elevation greater than 1,115.6 m (3,660 ft) above mean sea level.

The average discharge from the Shoshone River was 32.3 m^3/sec (1,141 cfs) for an 11 year period (U.S.G.S., 1968). The discharge normally fluctuates between a fall minimum of approximately 12.8 m^3/sec (430 cfs) and a spring maximum of 195.4 m^3/sec (6,900 cfs). Maximum recorded discharge was 373.8 m^3/sec (13,200 cfs) on 19 September 1961 and the minimum was 3.4 m^3/sec (120 cfs) on 21-23 January 1959. The drainage area of this river comprises 7,742 km^2 (2,989 mi^2) at an elevation greater than 1,117.9 m (3,635 ft) above mean sea level.

Permanent sampling stations were established during the study for each of the above tributaries. The Bighorn sampling site was located at lat. 44°45'31", long. 108°10'51", in NW1/4 NE1/4 SW1/4 Sec 9, T. 55 N., R. 94 W., off the right bank and 10.5 kilometers (6.5 miles) south of Kane, Wyoming. The location of the Shoshone River sampling station was lat. 44°51'45" long. 108°12'30", in E 1/2 Sec.6, T. 56 N., R. 95 W., off the right bank, 1.6 kilometers (1 mile) north of Kane, Wyoming and 2.4 kilometers (1.5 miles) upstream from its mouth.

A sampling station at the base of the dam was also established for the characterization of the effluent waters from the reservoir during the course of the study.

METHODS AND MATERIALS

Influent and Effluent Waters

Water samples and field measurements were taken at the various river stations at biweekly intervals for 1968 and weekly intervals for 1969, when possible, throughout the duration of this part of the study. Table II shows the dates and the rivers which were sampled.

All samples were obtained by lowering an 8-liter polyethylene bucket into the main current of the river. The container was rinsed well with the surface water prior to sampling. Upon collection, two 1-liter aliquots were collected in glass-stoppered Pyrex bottles. Immediately, one of the samples, to be used for heavy metal analyses, was preserved with 2 ml of 50% HCl (Rainwater and Thatcher, 1959). All storage bottles were rinsed twice before being filled with the water sample.

Water Chemistry

After returning to the laboratory, a portion (700 ml) of the untreated sample was filtered through Millipore® filters with a pore size of 0.45 microns. After filtering, the sample was placed back in the glass-stoppered Pyrex bottle, which had been rinsed with a small quantity of the filtrate. The remaining unfiltered water was placed in a 300 ml glass-stoppered Pyrex bottle and used in some of the subsequent analyses.

Measurement of hydrogen ion concentration was determined in the field and in the laboratory with an Orion specific ion meter (Model 401) and a Beckman Expanded Scale pH meter (Model 76), respectively.

Total alkalinity, chloride, fluoride, nitrate, nitrite, ammonia, total and soluble nitrogen, total phosphate, soluble and inorganic phosphate, sulfate, silica, calcium, magnesium, copper and turbidity determinations were made as described by the American Public Health Association (1965).

Total iron determinations were made according to the method of Collins and Diehl (1960). Manganese was determined by the leuco-base method as described by Strickland and Parsons (1968). The colorimetric equipment used in the various analyses was either a Bausch and Lomb "Spectronic 20" (Serial No. 4848 UB) or a Klett-Summerson (Model 800-3) colorimeter.

Total and soluble carbon fractions were determined by employing a Beckman Laboratory Carbonaceous Analyzer (Serial No. PI 1114).

Table II. The date and the river where water samples were collected (+) during the 1968 and 1969 sampling periods.

1968				1969			
Date	Bighorn Influent	Shoshone Influent	Discharge	Date	Bighorn Influent	Shoshone Influent	Discharge
2/22	+	+	+	1/ 3	*	*	+
3/ 7	+	+	+	1/18	*	+	+
3/28	+	+	+	2/ 1	*	+	+
4/11	+	+	+	2/15	*	+	+
5/ 4	+	+	+	3/ 1	*	+	+
5/18	+	+	+	3/17	+	+	+
6/ 1	+	+	+	3/31	+	+	+
6/12	+	+	+	4/ 7	+	+	+
6/24	+	+	+	4/14	+	+	+
7/15	+	+	+	4/21	+	+	+
8/ 1	+	+	+	4/28	+	+	+
8/19	+	+	+	5/ 5	+	+	+
9/23	+	+	+	5/12	+	+	+
10/ 7	+	+	+	5/22	+	+	+
10/19	+	+	+	5/28	+	+	+
11/ 9	+	+	+	6/ 3	+	+	+
11/23	+	+	+	6/10	+	+	+
12/ 7	+	+	+	6/17	+	+	+
12/20	*	+	+	6/24	+	+	+
				7/ 1	+	+	+
				7/ 8	+	+	+
				7/14	+	+	+
				7/21	+	+	+
				7/29	+	+	+
				8/ 5	+	+	+
				8/11	+	+	+
				8/18	+	+	+

* Samples were not collected because of ice cover.

Table III. The dates for each cruise and type of cruise made during the study period.

1968			1969			1970	
Cruise	(Type)	Date	Cruise	(Type)	Date	Cruise	Date
1	(L)	5/ 5	27	(L)	4/15	43	6/11
2	(S)	5/13	28	(S)	4/21	44	6/18
3	(S)	5/20	29	(S)	4/28	45	6/24
4	(S)	5/27	30	(S)	5/ 5	46	7/ 2
5	(L)	6/ 7	31	(L)	5/12	47	7/ 8
6	(S)	6/12	32	(S)	5/21	48	7/16
7	(S)	6/20	33	(S)	5/27	49	7/23
8	(S)	6/27	34	(S)	6/ 3	50	7/29
9	(S)	7/ 2	35	(S)	6/13	51	8/ 4
10	(L)	7/ 8	36	(L)	6/18	52	8/10
11	(S)	7/15	37	(S)	6/24	53	8/18
12	(S)	7/23	38	(S)	6/30	54	8/24
13	(S)	7/29	39	(S)	7/22	55	9/ 1
14	(L)	8/ 5	40	(L)	7/28	56	9/ 8
15	(S)	8/12	41	(S)	8/ 4		
16	(S)	8/19	42	(S)	8/11		
17	(S)	8/26					
18	(L)	9/ 3					
19	(S)	9/ 9					
20	(S)	9/17					
21	(S)	9/23					
22	(L)	10/ 2					
23	(S)	10/ 8					
24	(S)	10/14					
25	(S)	10/22					
26	(L)	11/ 2					

S = short cruise
L = long cruise

Sodium and potassium were determined by flame emission with a Beckman DU Flame Spectrophotometer. Zinc was determined by atomic absorption spectroscopy employing a Perkin-Elmer Atomic Absorption Unit (Model 303).

All of the above mentioned analyses were made within 96 hours after collection. Total alkalinity, the various forms of carbon, the various forms of phosphorus, total and soluble nitrogen, ammonia, nitrate, nitrite and laboratory pH determinations were made within 48 hours after collection.

Temperature and Conductivity

The temperature of the water sample upon collection was measured with a Gemware bucket thermometer (No. 297WA100).

The electrical resistance of each sample was measured with a YSI Conductivity Bridge (Model 31). An Industrial Instruments dipping cell (Model CEL 4) was used with the above conductivity bridge. The cell constant of the dipping cell was approximately 2.1 throughout the study.

The specific conductance of the water at 25 C was computed from the observed resistance and corrected for temperature and cell resistance.

Hydrology

Discharge measurements for the Bighorn and Shoshone Rivers were supplied by the U. S. Geological Survey. The gaging stations are located in the same areas where water samples were collected.

Records of the total discharge from the dam were furnished by the Bureau of Reclamation.

Reservoir

During the study all water samples and *in situ* measurements were taken during one of the fifty-six cruises at each station on Bighorn Lake. The length of the sampling season was usually five months (Table III). This study was carried out over three years (1968, 1969, and 1970). Due to the late date of receipt of the grant award it was not possible to sample the reservoir intensively in 1967. When possible, sampling periods were spaced at weekly intervals.

In 1968 and 1969 both "short cruises" and "long cruises" were made. A long cruise was made once a month and short cruises the rest of the month. On short cruises, transmissivity, temperature and conductivity measurements were made from the surface to the bottom

of the reservoir at 5 meter intervals at all sampling stations. In situ light measurements at depth intervals of 1 meter were obtained. Water samples were collected from the surface to the lower limit of the euphotic zone usually at 1 meter intervals. The pH of each sample was determined. Equal volumes of the euphotic zone samples were then composited and this composite was used for chlorophyll, nitrate, nitrite, ammonia, ortho-phosphate, total iron, manganese, copper, and zinc determinations. Also, a sample was taken from the composite for phytoplankton enumeration.

Everything determined on a short cruise was duplicated on a long cruise, but additional water samples for a more detailed chemistry study of the reservoir were collected at 10 meter intervals from the surface to the bottom of the reservoir. These samples were taken every 16.1 km starting with station 0 and analyzed for dissolved oxygen, pH, total alkalinity, chloride, fluoride, sulfate, nitrite, nitrate, ammonia, ortho-phosphate, silica, turbidity, potassium, sodium, calcium, and magnesium concentrations.

In 1970, transmissivity, temperature and conductivity were determined as for preceding years. Sampling procedures in the euphotic zone were similar to that of 1968 and 1969, but pH, oxygen, ortho-phosphate, nitrate, nitrite and ammonia concentrations were determined from the surface to the bottom of the reservoir at 10 meter intervals for all stations on all cruises.

Light

Vertical profiles of light attenuation were obtained by measuring in situ light intensities with a Gemware Photometer (Model No. 268WA310). This instrument included a gimbal-mounted deck photocell and an underwater photocell (both had matched photocells). Light intensity was measured from the surface and at 1 meter intervals until a depth at which only 1% of the total surface radiation was obtained.

A number of field and laboratory studies have shown that the compensation point for various phytoplankton organisms is reached at light intensities of about 1% total surface radiation (Verduin, 1964). Therefore, by definition the compensation point sets the lower limit of the euphotic zone.

The mean vertical extinction coefficients were computed as described by Hutchinson (1957). The extinction coefficient units are common log units per meter (k/m).

Light transmission was measured at 5 meter intervals from the surface with 1 meter and/or 10 centimeter Hydro Products transmissometer columns.

Kimball's (1928) tables of average radiation data for selected dates and latitudes were used in the calculations of primary productivity.

Temperature and Conductivity

Vertical in situ measurements for conductivity and temperature were made with a Beckman RB3-3341 Solu Bridge, calibrated for use with conductivity cell CEL-S02-VH2O-KP-X9. The latter incorporates a thermistor which serves a dual function as a component of an automatic temperature compensator for all conductivity ranges and as a primary element for temperature measurement.

Water Chemistry

A 3-liter Van Dorn Bottle was used to collect all water samples. All storage containers were rinsed with sample prior to filling.

One-liter samples were filtered through Millipore® filters with a pore size of 0.45 microns. After filtering, the samples were placed back in the storage containers, which were rinsed with a small quantity of the filtrate.

The methodology for the chemistry of the reservoir was the same as that used in characterizing the influent and effluent waters. A YSI Model 54 Oxygen Meter was used to the determination of dissolved oxygen. The instrument was calibrated by allowing the electrode system to equilibrate in a sample of known oxygen content.

Phytoplankton Standing Crop, Chlorophyll and Primary Productivity

The total cell volume per unit volume of water (mm^3/liter) was determined for each taxon in the phytoplankton community as follows. A 125 ml sample of the euphotic zone composite was preserved with Lugol's solution. Later in the laboratory, the algae were uniformly suspended in the solution, and a 10 ml settling chamber was filled with the phytoplankton sample. After 24 hours the sediment was examined with a Zeiss-Winkel inverted microscope. Morphological units representing each taxon were counted and linear dimensions measured with a Whipple micrometer disk. By assuming an appropriate geometrical shape, (i.e, sphere, prolate spheroid, etc.), the average cell volume per morphological unit was computed. A series of ratios involving sample volume, magnification and the number of fields counted were used to compute the cell volume per liter (Schwoerbel, 1970). Lund et al. (1958) have discussed the statistical validity of such direct count methods.

Identification of the phytoplankton was carried out to the species level where possible, but in some cases only generic designations were made. Algae were identified from both living and preserved material using the keys of Smith (1950), Prescott (1962), Hustedt (1930), Tiffany and Britton (1952) and Drouet (1959).

Fresh algal weight, in mg, was considered to be equivalent to cell volume in mm^3 (Strickland, 1960).

Chlorophyll a concentrations were determined by filtering (0.45 micron Millipore® filters) a known volume (usually 500 ml) of the euphotic zone composite water. The membrane was then dissolved in 5 ml of 90% acetone and allowed to stand in the dark for 24 hours. The solution was then centrifuged and the optical density of the supernatant was measured at 665 millimicrons using the Bausch and Lomb "Spectronic 20" colorimeter. The milligrams of chlorophyll a per cubic meter were calculated according to Odum et al. (1958).

The method of Ryther and Yentsch (1957) as modified by Martin (1967) was used to estimate primary productivity. This method assumes an average ratio between chlorophyll and productivity at light saturation and requires data on: (1) the average chlorophyll a concentration of the euphotic zone; (2) total solar radiation; (3) the extinction coefficient of the water column; and (4) average temperature of the euphotic zone for that day.

Hydrology

Stage, net inflow, total discharge and storage records for the reservoir were supplied by the Bureau of Reclamation.

Water exchange rates for the reservoir were computed by dividing the mean storage for a month by the mean monthly outflow.

RESULTS

Influent and Effluent Waters

Hydrology

Fluctuations in the discharge for the Bighorn River are more apparent than for the Shoshone River (Table IV). The natural flow of the Shoshone is regulated by Buffalo Bill reservoir while the Bighorn receives some regulation by Boysen reservoir. Both rivers are affected by diversions for irrigation and return flow from irrigated areas.

Table IV. Discharge (m^3/sec) for the influent and effluent waters of Bighorn Lake during 1968 and 1969 sampling periods.

1968				1969			
Date	Bighorn Influent	Shoshone Influent	Discharge	Date	Bighorn Influent	Shoshone Influent	Discharge
2/22	59.4	22.6	114.5	1/ 3	42.5	25.5	129.8
3/ 7	79.2	24.1	148.6	1/18	42.5	25.5	95.9
3/28	68.2	32.3	107.8	2/ 1	56.6	22.6	92.5
4/11	63.4	30.0	98.1	2/15	76.4	17.0	102.5
5/ 4	53.8	15.6	86.8	3/ 1	76.4	24.1	133.9
5/18	59.7	20.7	167.8	3/17	79.0	34.2	139.4
6/ 1	92.5	23.0	141.3	3/31	74.1	27.3	95.4
6/12	205.5	49.0	300.7	4/ 7	74.7	31.7	79.0
6/24	181.4	20.2	154.0	4/14	78.4	26.3	76.9
7/15	47.5	19.7	91.1	4/21	65.1	22.6	39.4
8/ 1	35.9	20.7	59.4	4/28	78.4	28.3	48.4
8/19	82.9	58.6	46.3	5/ 5	77.0	15.6	70.1
9/23	58.9	37.1	113.2	5/12	57.7	16.8	43.4
10/ 7	58.9	27.7	97.7	5/22	62.3	24.9	62.7
10/19	64.2	25.7	87.5	5/28	91.4	25.5	36.7
11/ 9	66.5	35.7	94.7	6/ 3	44.1	19.9	50.7
11/23	70.8	24.2	111.8	6/10	60.6	65.7	44.4
12/ 7	73.0	35.4	113.8	6/17	65.6	43.0	56.4
12/20	42.5	28.9	110.4	6/24	71.3	20.2	50.1
				7/ 1	169.8	28.9	122.8
				7/ 8	101.3	20.4	168.3
				7/14	62.3	19.4	165.6
				7/21	52.6	18.2	145.3
				7/29	43.0	18.6	104.3
				8/ 5	23.2	24.9	110.4
				8/11	22.1	47.3	102.5
				8/18	25.0	70.8	97.0

During 1968 and 1969, the Bighorn River had a mean monthly discharge of 2,191 m^3/sec, (77,342 cfs) while the discharge for the Shoshone River was 941 m^3/sec (32,158 cfs). Winter months usually had the lowest flows, whereas peak streamflows occurred in the spring (Table V). The peak inflows during June accounted for 13-19% of the total net inflow to the reservoir. The Bighorn River made up approximately 70% of the net inflow.

The major portion of the discharge from the dam was released through the power penstocks. Greater quantities of water were discharged during 1968 than any of the other years.

Temperature and Conductivity

The mean monthly temperatures for the influent and effluent waters are given in Figure 4. The cycle of temperature in the discharge water lagged behind the influent water temperature.

Temperatures of the influent streams were at or near freezing through most of December, usually all of January and most of February. From the latter part of February there was a rise in temperature until maximal temperatures were attained in July and August. The highest recorded temperature was 28.2 C for the Bighorn River on 5 August 1969.

In contrast, the effluent water temperature never reached freezing. Minimum temperatures appeared in March and April (2.5 C) followed by a maximum in September (16.0 C, 1968; 12.5 C, 1969).

The effect of impoundment and deep water withdrawal was to displace the maximum and minimum temperatures two to four months behind the influent temperatures and to increase the minimum temperatures above those of the influents.

Figure 5 compares the conductivity of the influent waters with that of the discharge. Conductivity of the Bighorn River never exceeded 1,250 micromhos while 1,500 micromhos was the high recorded for the Shoshone River.

Extremely large fluctuations in conductivity were noted for the Shoshone River whereas most of the values for the Bighorn River were around 900 micromhos. Values were minimal in the Bighorn River during periods of high streamflow in May and June. Maximal conductivity values for the Bighorn River occurred in late summer and early fall periods. The relationship between specific conductance and discharge is illustrated in Figure 6.

Table V. Total monthly discharge (m^3/sec) for the influent and effluent waters of Bighorn Lake during 1968 and 1969 sampling periods.

	1968				1969		
Month	Bighorn Influent	Shoshone Influent	Discharge	Month	Bighorn Influent	Shoshone Influent	Discharge
Jan	1,572	753	4,714	Jan	1,373	880	3,136
Feb	1,873	591	3,434	Feb	2,018	640	2,943
Mar	2,214	888	3,820	Mar	2,370	739	3,665
Apr	1,851	808	3,064	Apr	2,085	751	1,846
May	1,848	670	3,589	May	2,102	485	1,492
June	5,582	983	7,010	June	2,918	1,200	2,605
July	1,791	609	2,405	July	2,206	1,148	4,233
Aug	1,918	1,325	1,905	Aug	741	527	3,135
Sept	2,023	1,035	3,110	Sept	937	692	2,739
Oct	1,780	874	2,997	Oct	2,935	1,598	2,838
Nov	2,014	973	3,445	Nov	3,665	1,386	2,635
Dec	1,818	1,025	3,425	Dec	2,969	1,292	3,292

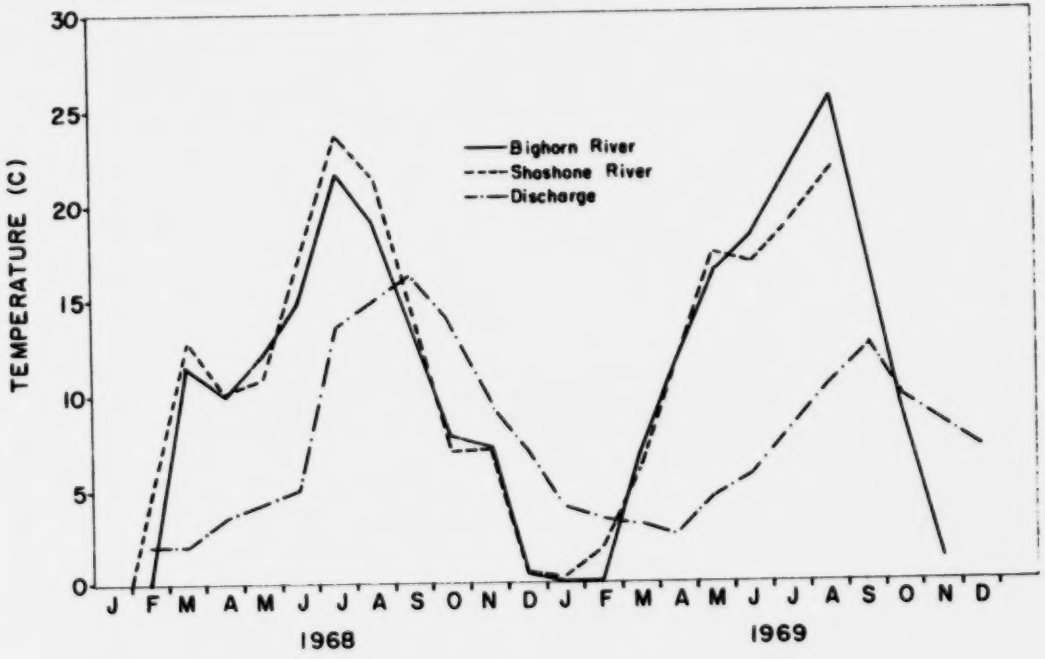

Figure 4. Monthly average of temperatures (C) for the influent and effluent waters of Bighorn Lake during the 1968 and 1969 sampling periods (September - December values supplied by the U.S.G.S.).

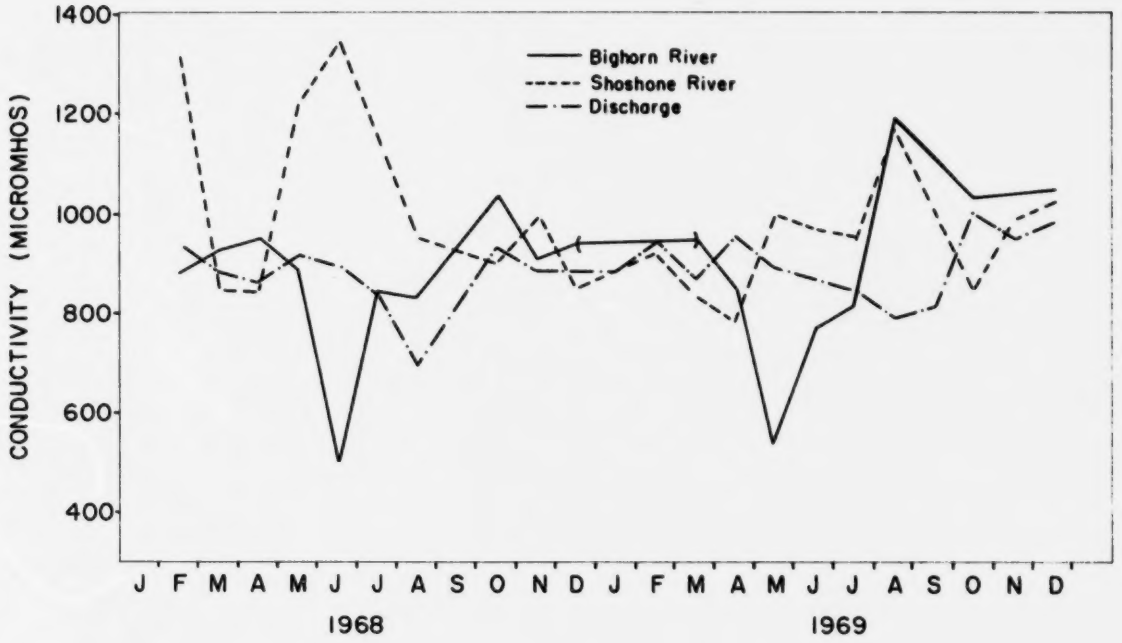

Figure 5. Monthly average of specific conductance (micromhos) for the influent and effluent waters of Bighorn Lake during the 1968 and 1969 sampling periods (September - December values supplied by the U.S.G.S.).

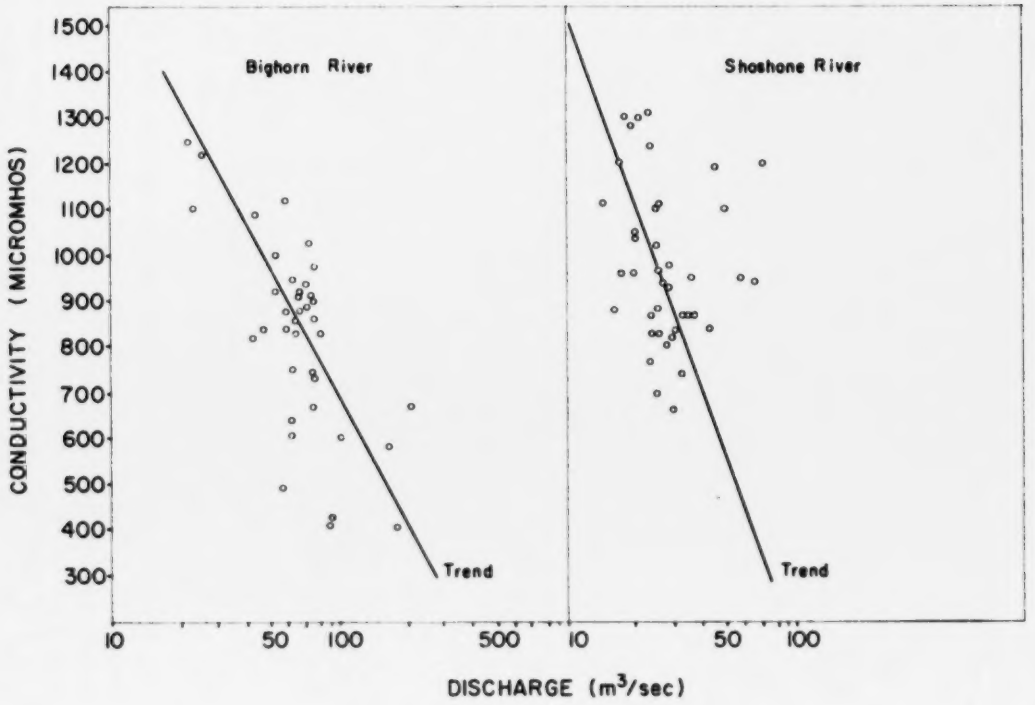

Figure 6. Relationship between specific conductance (micromhos) and mean discharge (m^3/sec) for the influent waters of Bighorn Lake during the 1968 and 1969 sampling periods.

The two to four month lag is again evident between minimum and maximum values of conductivity when influent waters (particularly the Bighorn River) and the discharge are compared (Fig. 5).

Water Chemistry

The composition of the influent waters is what would be expected from rivers draining sedimentary rocks under semi-arid conditions (Hem, 1959). The range and mean water chemistry are presented in Tables VI and VII. The cations in highest concentration, calcium and sodium, were approximately equal in concentration followed by magnesium and potassium. Sulfate was the anion in highest concentration followed by bicarbonate and chloride.

Discharge-weighted means (for 1968 and 1969) of the major ions of the influent streams and the discharge are given in Table VIII. Discharge-weighted means were computed by multiplying the discharge for a given sampling period by the concentrations of individual constituents for the period and dividing the sum of the products by the sum of the discharges. Overall, water discharge from the dam was slightly lower in dissolved solids than the weighted average of the influents. Sodium, potassium, chloride and sulfate appeared to behave in a conservative manner. The downstream decrease in concentration of these ions, particularly sodium, probably was due to dilution by rainfall and/or run-off from snow-fed tributaries. In 1969, there was a decrease in calcium concentration in the discharge compared to an increase in magnesium, but a decrease in both ions occurred in 1968. These elements were determined using a complexometric titration which, because of the inherent errors of the method (A.P.H.A., 1965), could possibly account for the different results between the two years.

Table IX presents values of the various carbon, nitrogen and phosphorus fractions averaged from 22 samples collected between 19 August 1968 and 18 August 1969 from the influent and effluent waters.

Of the total amount of nitrogen that entered the reservoir 75% was discharged. A large decrease in particulate nitrogen was evident from a comparison of influent and effluent concentrations. The concentration of total inorganic nitrogen leaving the reservoir was essentially the same as that entering. More nitrate was discharged than entered, which indicates nitrification and nitrogen fixation were in excess of nitrogen assimilation and denitrification.

Only 14% of the phosphorus that entered the reservoir was discharged. The greatest loss was in particulate phosphorus.

Table VI. Range and mean of water chemistry for the influent and effluent waters of Bighorn Lake during the 1968 sampling periods.

	Bighorn Influent	Shoshone Influent	Discharge
Ca^{++} (meq/1)	1.45-4.66	1.40-7.62	2.00-4.98
	3.66	4.76	3.82
Mg^{++} (meq/1)	0.49-5.17	1.34-3.84	0.91-2.60
	2.09	2.42	1.86
Na^{+} (meq/1)	1.12-4.75	1.72-6.84	1.99-4.25
	3.35	4.84	3.23
K^{+} (meq/1)	0.06-0.27	0.09-0.22	0.08-0.42
	0.14	0.15	0.15
HCO_3^{-} (meq/1)	1.92-3.82	3.24-4.76	2.81-3.97
	3.03	3.90	3.18
Cl^{-} (meq/1)	0.12-0.57	0.13-0.52	0.20-0.41
	0.35	0.30	0.29
$SO_4^{=}$ (meq/1)	1.04-8.28	3.75-13.54	5.25-7.42
	5.95	8.35	6.17
F^{-} (meq/1)	0.02-0.11	0.02-0.11	0.02-0.10
	0.04	0.05	0.04
Soluble Organic C (mg/1)	1.2 -14.2	1.5- 11.4	0.0 -10.3
	7.7	6.7	6.4
Particulate C (mg/1)	0.8 -31.7	0.3 - 7.4	0.0 - 3.9
	7.0	3.7	2.0
NO_3^{-} -N (mg/1)	0.09-0.79	0.08-1.67	0.25-0.83
	0.35	0.85	0.54
NO_2^{-} -N (mg/1)	0.003-0.028	0.003-0.029	0.001-0.017
	0.008	0.011	0.005
NH_3 -N (mg/1)	0.00-1.36	0.00-0.66	0.00-0.50
	0.35	0.28	0.17
Soluble Organic NH_3-N (mg/1)	0.00-0.95	0.02-1.49	0.00-1.50
	0.33	0.52	0.47
Particulate NH_3-N (mg/1)	0.00-1.88	0.00-0.45	0.00-1.18
	0.34	0.06	0.09
Ortho-$PO_4^{\equiv}$ (mg/1)	0.00-0.40	0.00-0.64	0.00-0.16
	0.11	0.12	0.04
Soluble Organic $PO_4^{\equiv}$ (mg/1)	0.00-0.35	0.00-1.10	0.00-0.16
	0.04	0.06	0.02
Particulate $PO_4^{\equiv}$ (mg/1)	0.00-3.39	0.00-2.08	0.00-0.21
	1.90	0.47	0.04

Table VI.(Cont'd)

	Bighorn Influent	Shoshone Influent	Discharge
Turbidity (J.T.U.)	30-4,900 816	36-2,220 434	4-30 13
Silica (mg/l)	6.3-12.9 9.4	7.6-18.5 13.8	6.7-14.0 10.0
Total Iron (mg/l)	0.004-0.885 0.138	0.016-0.440 0.129	0.003-0.022 0.009
Mn^{++} (mg/l)	0.004-0.119 0.021	0.001-0.077 0.025	0.000-0.009 0.004
Cu^{++} (µg/l)	0.70-3.80 1.60	0.80-2.80 1.40	0.80-1.70 1.10
Zn^{++} (mg/l)	0.007-0.232 0.094	0.010-0.260 0.084	0.006-0.258 0.057
Conductance (micromhos)	412-1,125 837	818-1,684 1,062	669-932 870
pH Range	7.49-8.55	7.78-8.46	6.98-8.10

Table VII. Range and mean of water chemistry for the influent and effluent waters of Bighorn Lake during the 1969 sampling periods.

	Bighorn Influent	Shoshone Influent	Discharge
Ca^{++} (meq/1)	2.08-5.48 3.43	1.82-4.67 3.76	2.88-4.43 3.71
Mg^{++} (meq/1)	0.49-2.80 1.69	0.86-2.73 1.95	1.46-3.38 2.02
Na^{+} (meq/1)	1.77-6.80 3.51	2.19-6.20 4.16	2.73-4.50 3.53
K^{+} (meq/1)	0.06-0.17 0.12	0.06-0.16 0.12	0.06-0.16 0.12
HCO_3^{-} (meq/1)	1.41-3.45 2.52	1.81-4.60 3.15	2.25-3.70 3.05
Cl^{-} (meq/1)	0.17-0.56 0.35	0.14-0.69 0.31	0.27-0.45 0.34
$SO_4^{=}$ (meq/1)	2.42-7.50 5.03	3.10-8.44 5.83	4.33-6.21 5.47
F^{-} (meq/1)	0.02-0.05 0.03	0.02-0.06 0.04	0.02-0.06 0.04
Soluble Organic C (mg/1)	4.4 -20.0 9.6	4.8 -24.9 9.7	5.3 -23.0 9.5
Particulate C (mg/1)	0.0 -39.6 10.5	0.0 -27.0 8.1	0.0 -30.8 5.0
NO_3^{-} -N (mg/1)	0.12-0.78 0.40	0.00-1.53 0.79	0.00-0.74 0.55
NO_2^{-} -N (mg/1)	0.002-0.011 0.005	0.000-0.019 0.011	0.000-0.015 0.004
NH_3 -N (mg/1)	0.04-0.71 0.25	0.07-0.71 0.26	0.02-0.55 0.21
Soluble Organic NH_3-N (mg/1)	0.00-0.87 0.19	0.00-0.87 0.26	0.01-0.56 0.18
Particulate NH_3-N (mg/1)	0.04-2.18 0.67	0.00-2.24 0.46	0.00-0.75 0.21
Ortho-$PO_4^{\equiv}$ (mg/1)	0.00-1.55 0.11	0.00-0.28 0.08	0.00-0.17 0.04
Soluble Organic $PO_4^{\equiv}$ (mg/1)	0.00-0.04 0.00	0.00-0.12 0.00	0.00-0.14 0.00
Particulate $PO_4^{\equiv}$ (mg/1)	0.00-3.22 0.68	0.00-1.30 0.55	0.00-0.16 0.05

Table VII.(Cont'd)

	Bighorn Influent	Shoshone Influent	Discharge
Poly-$PO_4^{\equiv}$ (mg/l)	0.00-0.43 0.02	0.00-0.18 0.05	0.00-0.35 0.05
Turbidity (J.T.U.)	59-3,600 631	22-2,540 371	0-36 10
Silica (mg/l)	6.3-19.4 9.1	8.3-17.6 13.8	6.0-12.8 10.5
Total Iron (mg/l)	0.001-4.015 1.290	0.001-3.900 1.390	0.000-0.463 0.052
Mn^{++} (mg/l)	0.000-2.145 0.265	0.001-0.560 0.182	0.000-0.300 0.030
Cu^{++} (µg/l)	0.5-22.0 3.1	0.5-21.0 2.6	0.0-6.0 1.3
Zn^{++} (mg/l)	0.000-0.178 0.048	0.004-0.169 0.038	0.004-0.058 0.022
Conductance (micromhos)	427-1,247 826	507-1,315 941	692-971 877
pH Range	7.33-8.63	7.35-8.56	6.81-8.31

Table VIII. Discharge-weighted chemical composition (meq/1) of the influent and effluent waters of Bighorn Lake during 1968 and 1969.

	1968								
	Ca	Mg	Na	K	HCO_3	Cl	SO_4	F	Sum
Bighorn (B.H.)	3.64	2.10	3.22	0.13	2.94	0.33	5.37	0.04	17.77
Shoshone (Shos.)	4.69	2.32	4.72	0.15	3.91	0.30	8.00	0.04	24.13
Weighted Average of B.H. & Shos.	3.94	2.17	3.65	0.14	3.22	0.33	6.12	0.04	19.61
Discharge	3.89	1.91	3.27	0.14	3.18	0.30	6.11	0.03	18.83
Percent change	-1.3	-11.9	-10.4	0.0	-1.3	-9.1	-0.2	-25.0	-4.0

	1969*								
	Ca	Mg	Na	K	HCO_3	Cl	SO_4	F	Sum
Bighorn (B.H.)	3.80	1.90	3.61	0.10	2.94	0.37	5.65	0.02	18.39
Shoshone (Shos.)	4.02	2.06	3.87	0.11	3.62	0.33	5.83	0.03	19.87
Weighted Average of B.H. & Shos.	3.87	1.95	3.69	0.11	3.16	0.36	5.70	0.03	18.87
Discharge	3.74	2.05	3.70	0.11	3.14	0.31	5.79	0.03	18.87
Percent change	-3.4	+4.9	+0.3	0.0	-0.6	-13.9	+1.6	0.0	0.0

* September-December data supplied by the U.S.G.S.

Table IX. The carbon (mg/l C), nitrogen (mg/l N) and phosphate (mg/l $PO_4^{\equiv}$) balances of Bighorn Lake for the period between 19 August 1968 and 18 August 1969.

	Total Organic -N	Particulate Organic -N	Soluble Organic -N	NH_3 -N^3	NO_2 -N^2	NO_3 -N^3	Total Inorganic -N	Total Inorganic + Organic -N
Bighorn (B.H.)	0.91	0.68	0.23	0.30	0.006	0.40	0.71	1.62
Shoshone (Shos.)	0.75	0.47	0.29	0.28	0.01	0.89	1.18	1.93
Weighted Average of B.H. & Shos.	0.86	0.62	0.25	0.29	0.007	0.55	0.85	1.71
Discharge	0.44	0.23	0.21	0.23	0.004	0.61	0.84	1.28
Percentage change	-49	-63	-16	-20	-43	+11	-1	-25

	Total $-PO_4$	Particulate $-PO_4$	Ortho $-PO_4$
Bighorn (B.H.)	0.926	0.625	0.104
Shoshone (Shos.)	0.792	0.553	0.077
Weighted Average of B.H. & Shos.	0.886	0.603	0.096
Discharge	0.123	0.040	0.031
Percentage change	-86	-93	-68

	Total Organic -C	Particulate Organic -C	Dissolved Organic -C
Bighorn (B.H.	18.75	9.82	8.93
Shoshone (Shos.)	16.50	7.20	9.30
Weighted Average of B.H. & Shos.	16.57	7.22	9.27
Discharge	12.51	3.79	8.72
Percentage change	-24	-47	-6

Significant correlations existed between high turbidity and high total phosphorus for both the Bighorn ($r = 0.79$; $P = 0.01$) and Shoshone ($r = 0.71$; $P = 0.01$) Rivers. A positive correlation was also found between turbidity and total nitrogen for the Bighorn ($r = 0.66$; $P = 0.01$), however, this relationship for the Shoshone River was not statistically significant.

Figure 7 presents a comparison of streamflows and turbidities for influent and effluent waters. When run-off into the reservoir was high, especially in the case of the Bighorn River, a corresponding increase in turbidity was observed, but turbidity for the discharge never exceeded 30 Standard Jackson Turbidity Units.

High values of ortho-phosphate as well as total phosphate are associated with high turbidity (Fig. 8). This may indicate that a base exchange equilibrium occurred between the water and the suspended sediments, releasing ortho-phosphate from the sediments.

The most significant change in the carbon balance of the influent and effluent waters (Table IX) was the decrease in particulate carbon. Dissolved organic carbon was essentially the same in the discharge as in the influent streams.

Data concerning the heavy metal analyses are given in Table X. There was a decrease in concentration of these elements in the discharge compared to the influent streams. The greatest decrease was in iron followed by manganese. Copper appeared to be the most mobile of all the heavy metals. The ratio of iron to manganese was less in the discharge than in the influents. The ratio of copper to zinc was higher in the discharge than in the influent water. The major cause of decrease in concentration of these metals was attributed to the settling out of suspended sediments that were carried into the reservoir.

Table X. Iron, manganese, copper and zinc (mg/l) budget of Bighorn Lake during the 1968 and 1969 sampling periods.

	Fe	Mn	Fe/Mn	Cu	Zn	Cu/Zn
Bighorn (B.H.)	1.052	0.152	6.92	0.0025	0.086	0.03
Shoshone (Shos.)	1.000	0.124	8.67	0.0023	0.067	0.03
Weighted Average of B.H and Shos.	1.036	0.144	7.19	0.0024	0.080	0.03
Discharge	0.034	0.022	1.55	0.0015	0.023	0.07
Percentage Change	-97	-86		-40	-71	

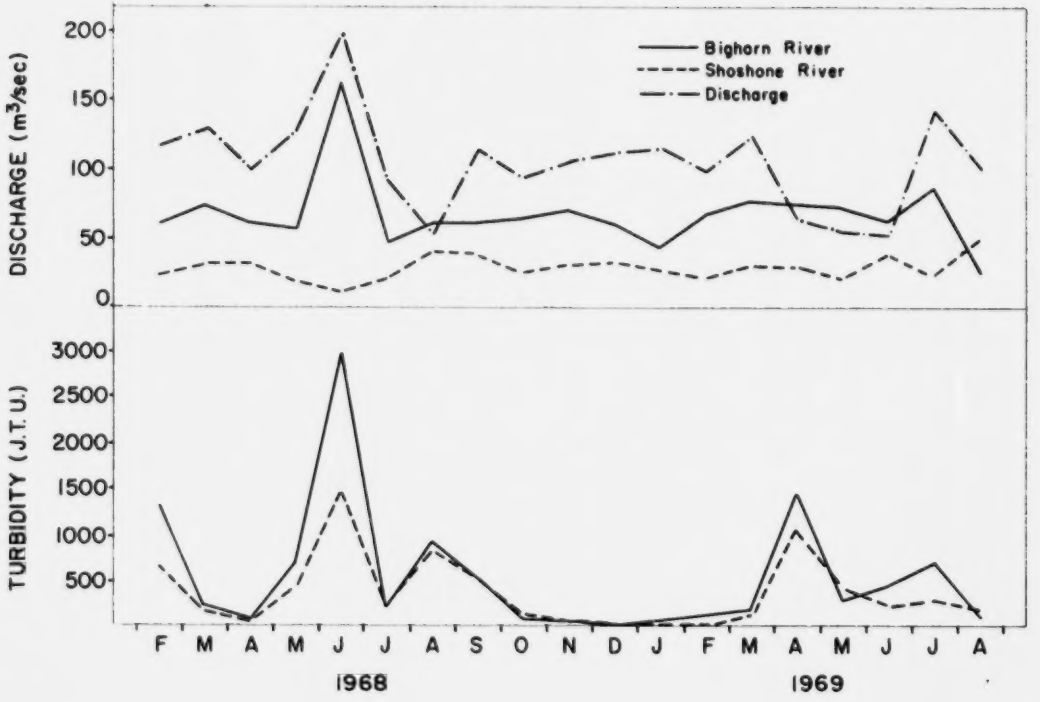

Figure 7. Seasonal fluctuations of mean discharge (m^3/sec) and turbidity (Standard Jackson Turbidity Units) for the influent and effluent waters of Bighorn Lake during the 1968 and 1969 sampling periods.

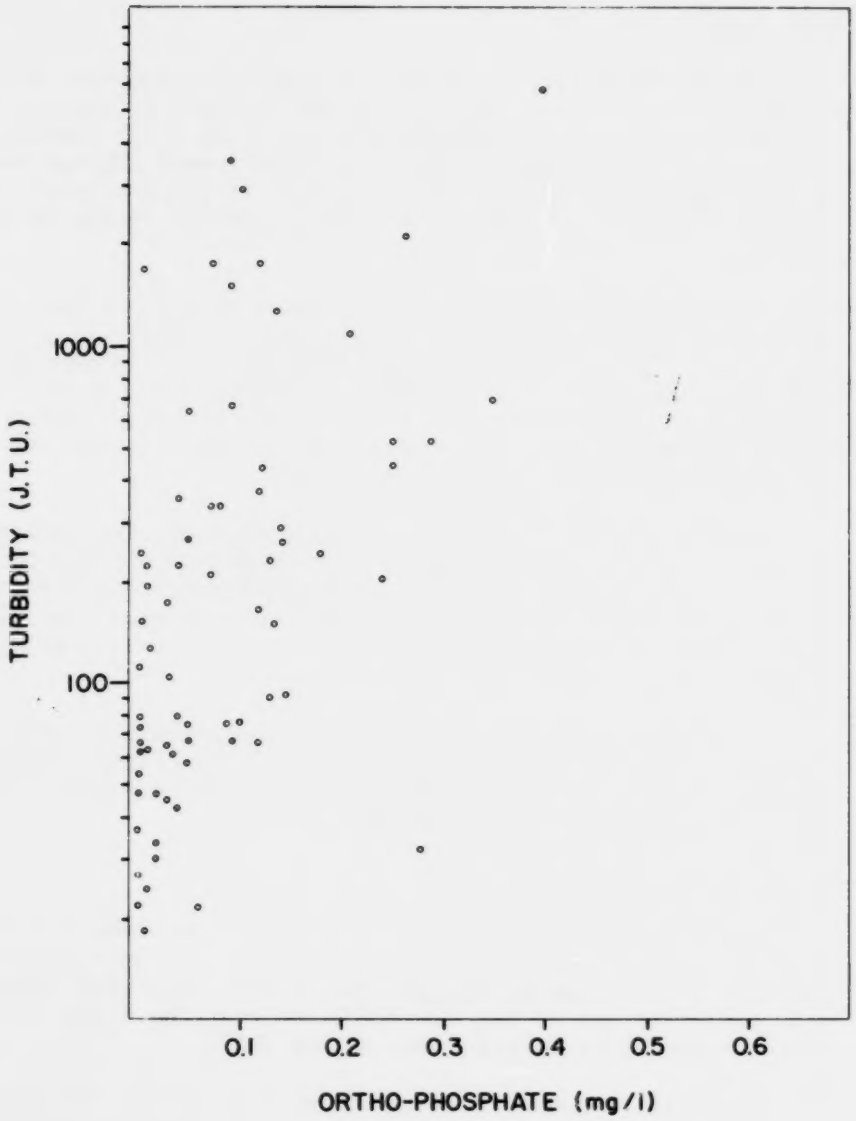

Figure 8. Relationship between turbidity (Standard Jackson Turbidity Units) and ortho-phosphate (mg/l $PO_4^{\equiv}$) for the Bighorn and Shoshone Rivers.

Reservoir

Hydrology

Due to excessive inflow to the reservoir, Bighorn Lake was filled to maximum capacity in 1967. Sixty-one percent of the total net inflow for 1967 occurred during May, June and July. Twenty percent of the total discharge for the year was diverted through the spillway in July because of the excessive run-off to the reservoir in the preceding months. These high discharges caused damage to the spillway tunnel.

Inflow, discharge and storage change data for water years 1968, 1969 and 1970 are given in Table XI. Two extremes are illustrated, with a negative storage value for 1968 and positive storage values for 1969 and 1970. The negative value in 1968 was due to the fact that the total discharge had to be greater than the total inflow in order to attain and maintain water levels below the spillway elevation to facilitate repair of the spillway tunnel.

Reservoir water level fluctuations for 1969 and 1970 were fairly constant. There was a spring rise of 20 meters (66 ft) to reach a maximum in July followed by receding water levels to a minimum in February and March (Fig. 9). However, the reservoir was in a filling stage during the study and water levels were not indicative of normal operation until 1970.

The annual water exchange rates for Bighorn Lake were 0.3 in 1968, 0.4 in 1969 and 0.5 in 1970 (Table XII). This illustrates that as water levels increased, the retention time of a given mass of water within the reservoir became greater.

Light

The transmittance of light in Bighorn Lake ranged from 3 to 100% T/10 cm column. The influent waters had the lowest clarity, but as the water flowed toward the dam the clarity increased (Fig. 10). The mean turbidity was 10 and 414 J.T.U. at stations 0 and 5, respectively, while transmission of light was 92 and 59%.

The significant correlation ($r = -0.99$; $P = 0.01$) between transmission and turbidity is evident (Fig. 11). The regression equation between transmission and turbidity was calculated:

$$\text{Transmission (\% T/10 cm)} = -20.9T + 112.1 \qquad R^2 = 0.98$$

where T equals the common log of the turbidity expressed as J.T.U..

Table XI. Inflow, discharge and storage change ($X10^5$ m^3) in Bighorn Lake for the water years ending 30 September 1968, 30 September 1969 and 30 September 1970.

	1968												
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Total
Net Inflow	2,375	2,580	2,466	2,329	2,628	2,853	2,408	2,490	6,542	2,354	2,794	2,686	34,505
Total Discharge	2,240	2,703	3,835	4,064	2,960	3,268	2,638	3,094	6,043	2,074	1,643	2,681	37,243
Storage Change	+135	-123	-1,369	-1,735	-332	-415	-230	-604	+499	+280	+1,151	+5	-2,738

	1969												
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Total
Net Inflow	2,662	2,840	2,483	2,034	2,389	2,861	2,625	2,615	4,018	3,320	1,561	1,837	31,245
Total Discharge	2,587	2,970	2,953	2,704	2,537	3,159	1,592	1,286	2,266	3,157	2,703	2,361	30,275
Storage Change	+75	-130	-470	-670	-148	-298	+1,033	+1,329	+1,752	+163	-1,142	-524	+970

	1970												
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Total
Net Inflow	2,407	2,334	1,880	1,719	2,286	2,439	1,945	3,448	5,863	3,643	1,334	1,906	31,204
Total Discharge	2,450	2,272	2,838	2,919	2,487	1,453	795	1,681	3,856	5,032	1,781	1,383	28,947
Storage Change	-43	+62	-958	-1,200	-201	+986	+1,150	+1,767	+2,007	-1,389	-447	+523	+2,257

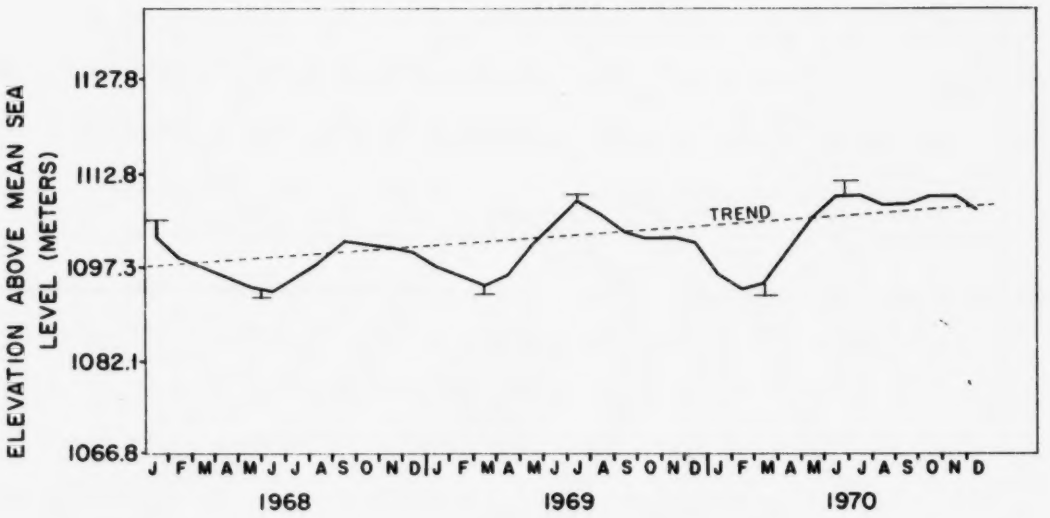
ELEVATION ABOVE MEAN SEA LEVEL (METERS)
1127.8
1112.8
1097.3
1082.1
1066.8
TREND
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
1968
1969
1970

Figure 9. Range and mean water levels of Bighorn Lake during 1968, 1969 and 1970 (Bureau of Reclamation Data).

Table XII. Water exchange rates (days) in Bighorn Lake for 1968, 1969, and 1970.

Month	Average Storage ($X10^6$ m^3)	Average Discharge ($X10^6$ m^3/day)	Exchange Rate (days)
		1968	
January	1,071.7	13.1	81.9
February	982.7	10.2	96.4
March	952.4	8.7	109.4
April	922.9	8.8	105.0
May	877.1	10.0	88.0
June	866.9	20.1	43.1
July	927.8	6.9	134.5
August	968.7	5.5	177.2
September	1,053.1	8.9	118.1
October	1,043.9	8.3	125.5
November	1,046.8	9.9	105.9
December	1,027.4	9.5	108.0
Mean			107.8
Monthly			3.6
Annual			0.3
		1969	
January	951.5	8.7	109.3
February	921.5	9.1	101.9
March	882.8	10.2	86.8
April	917.8	5.3	173.3
May	1,044.2	4.1	252.2
June	1,175.9	7.5	156.0
July	1,298.8	11.8	110.5
August	1,198.4	8.7	137.7
September	1,105.5	7.9	140.7
October	1,091.3	7.9	138.5
November	1,085.6	7.6	143.6
December	1,049.5	9.1	114.9
Mean			138.8
Monthly			4.6
Annual			0.4

Table XII. (Cont'd)

Month	1970 Average Storage ($X10^6$ m^3)	1970 Average Discharge ($X10^6$ m^3/day)	1970 Exchange Rate (days)
January	925.8	9.4	98.5
February	865.2	8.9	97.6
March	875.9	4.7	187.2
April	1,022.4	2.6	386.5
May	1,152.7	5.4	213.0
June	1,323.2	12.8	103.1
July	1,346.1	16.2	83.1
August	1,281.3	5.7	223.5
September	1,281.3	4.6	278.5
October	1,332.9	6.2	215.9
November	1,331.6	7.5	177.3
December	1,296.6	9.3	139.0
Mean			183.6
Monthly			6.1
Annual			0.5

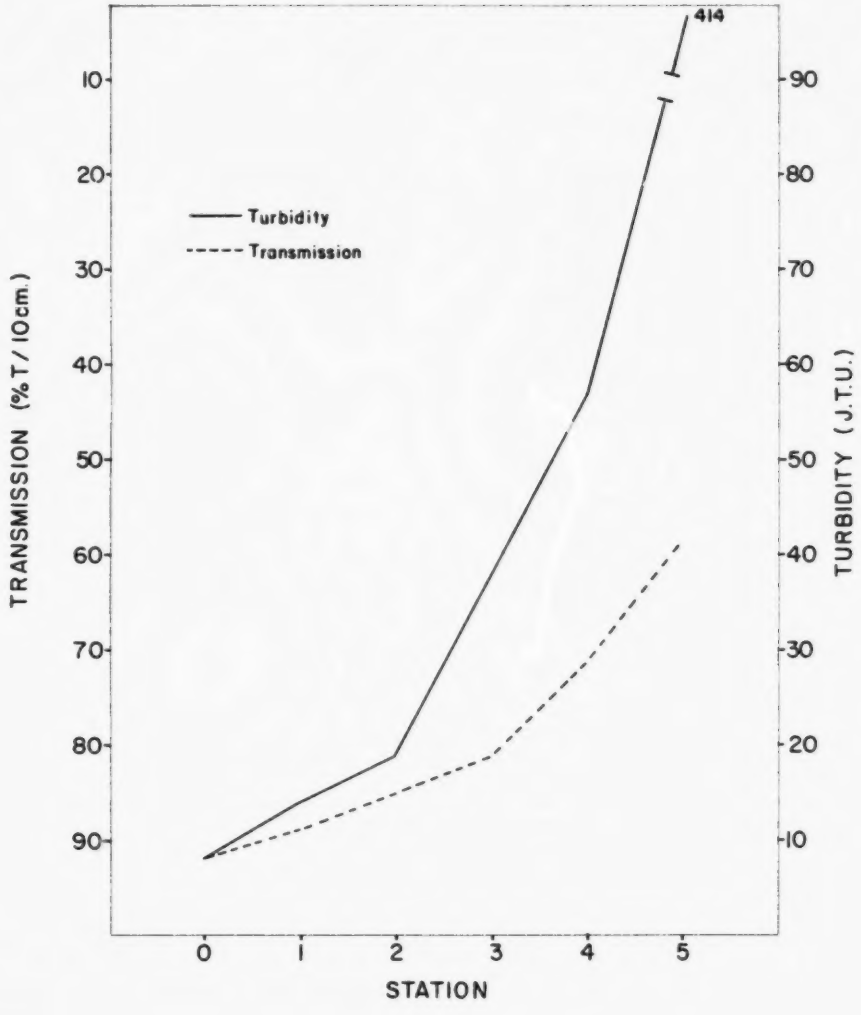

Figure 10. Water clarity in Bighorn Lake expressed as the mean turbidity (Standard Jackson Turbidity Units) and light transmittance (% T/10 cm) at each sampling station during the study.

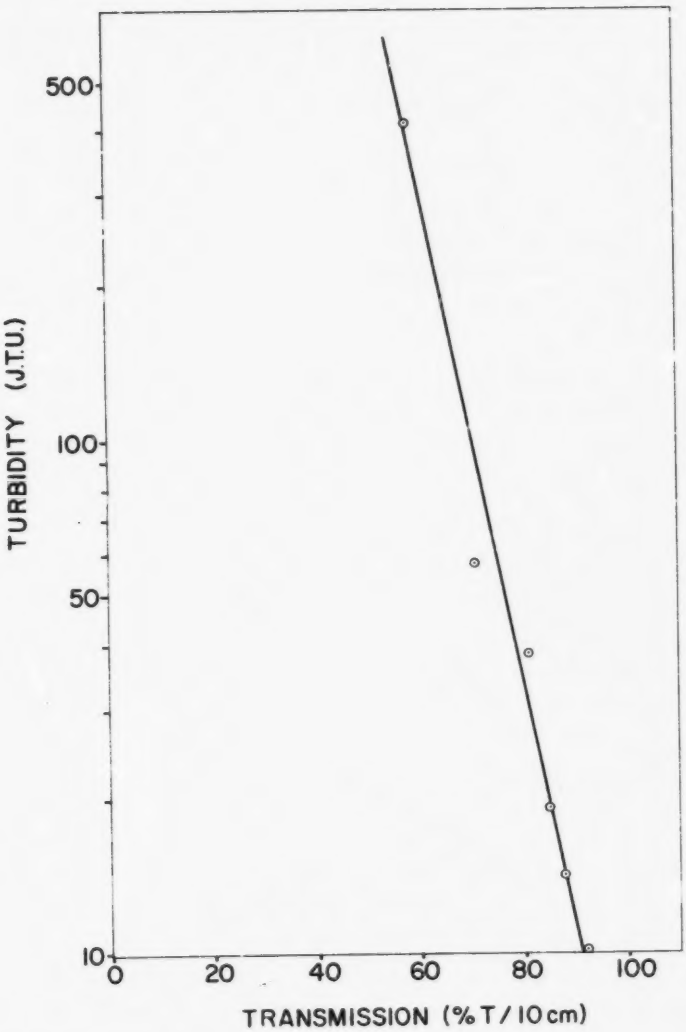

Figure 11. Relationship between turbidity (Standard Jackson Turbidity Units) and light transmittance (% T/10 cm). A point represents a mean of all data at a given station, Bighorn Lake.

It has been pointed out by many workers, including Neel et al. (1963), that because of impoundment there is a striking reduction of turbidity as the water mass flows through the reservoir. More detailed patterns of water clarity, utilizing transmission data for 1969, are depicted in Figure 12. Turbidity for the influent streams was significantly reduced within the upper 32.2 km (20 mi) of the reservoir. Seasonal changes in the clarification process are given with peak inflow occurring in June, and minimal inflow during August.

Figure 13 gives the average euphotic zone extinction coefficients of total visible light measured at each station for each year of sampling. It is noted that stations 0, 1, 2, 3 and 4 have coefficients ranging between 0.35 and 1.50, but the range between stations 4 and 5 is of a greater magnitude for all years except 1970. Station 5 consistently attenuated light at a much greater rate than any of the other sampling stations.

A t-test was used to compare the average extinction coefficients of the six stations. Between 13 and 25 degrees of freedom were available for each test between each of the possible 12 pairs of stations within a given year. The statistical analyses showed a significant difference in the average transparency conditions among all stations, except for stations 2, 3 and 4 during 1970.

A t-test was also used to compare the 1968, 1969 and 1970 average transparencies for all stations. Between 178 and 250 degrees of freedom were available for each test. A significant difference was found between the mean extinction coefficients for all years except between 1969 and 1970.

When all the data (n= 336) are used, the correlation ($r = -0.19$; $P = 0.01$) between extinction and reservoir stage indicated that as water levels rose, light extinction became less.

A summary of underwater light conditions at all sampling stations during the study is presented in Figure 14.

Temperature and Conductivity

Figure 15 shows the thermal regime at station 0 during the 1968, 1969 and 1970 sampling periods. In general, spring temperatures were lower during 1969 than on comparable dates for 1968 and 1970. Mid-summer surface temperatures for all years were greater than 21.0 C.

On 5 May 1968, the surface temperature was 7.8 C. Only slight thermal stratification was evident as the temperature declined with depth to 3.3 C at elevation 1,025. Below 995 meters there was an increase in temperature near the bottom attributed to heat exchange

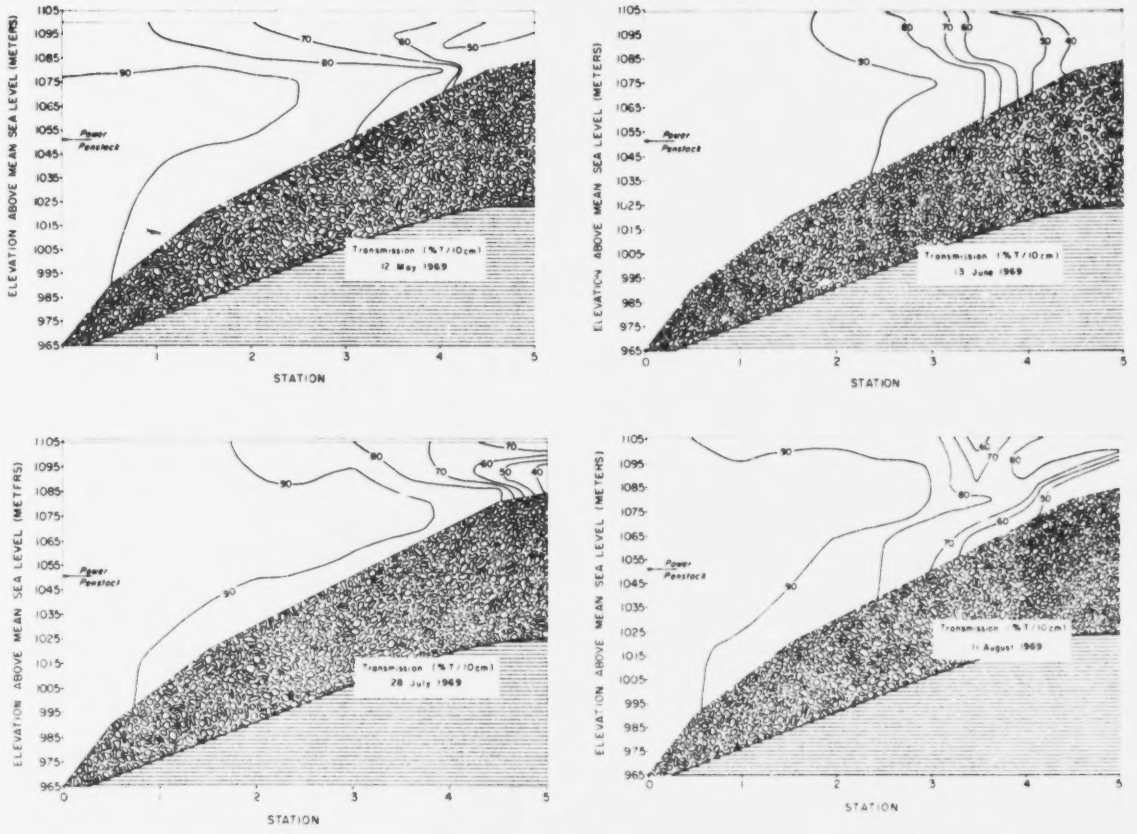

Figure 12. Seasonal and longitudinal distribution of suspended sediment, utilizing transmission data (% T/10 cm) for Bighorn Lake during 1969.

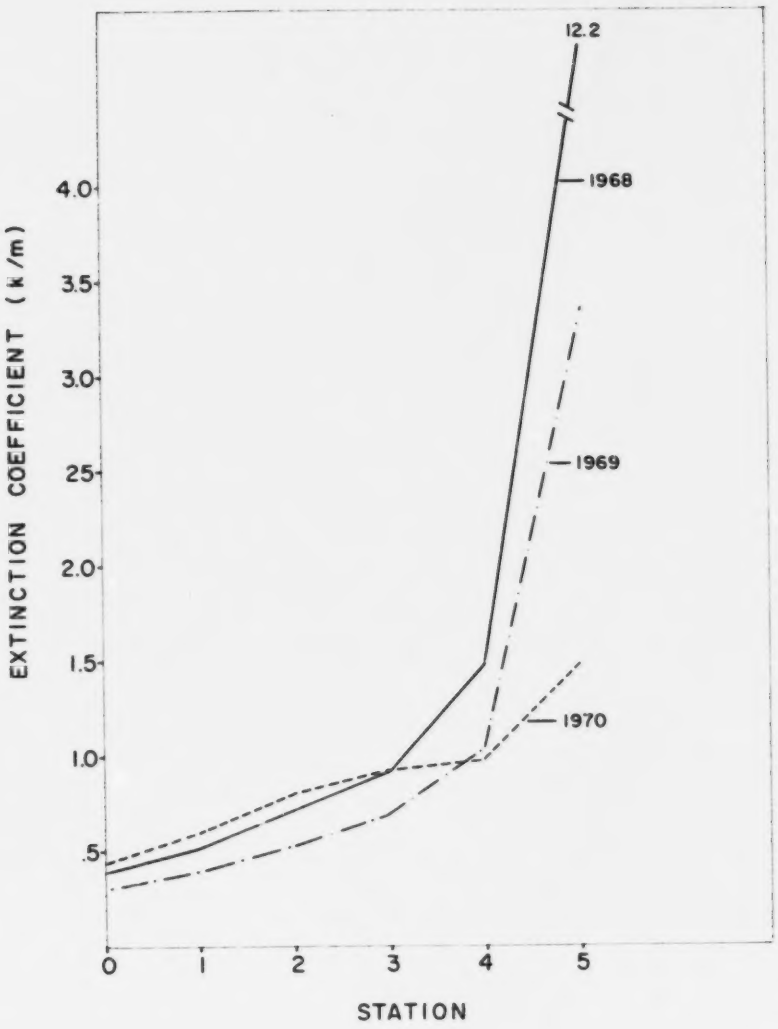

Figure 13. Average extinction coefficients (k/m) at each station for each year, Bighorn Lake.

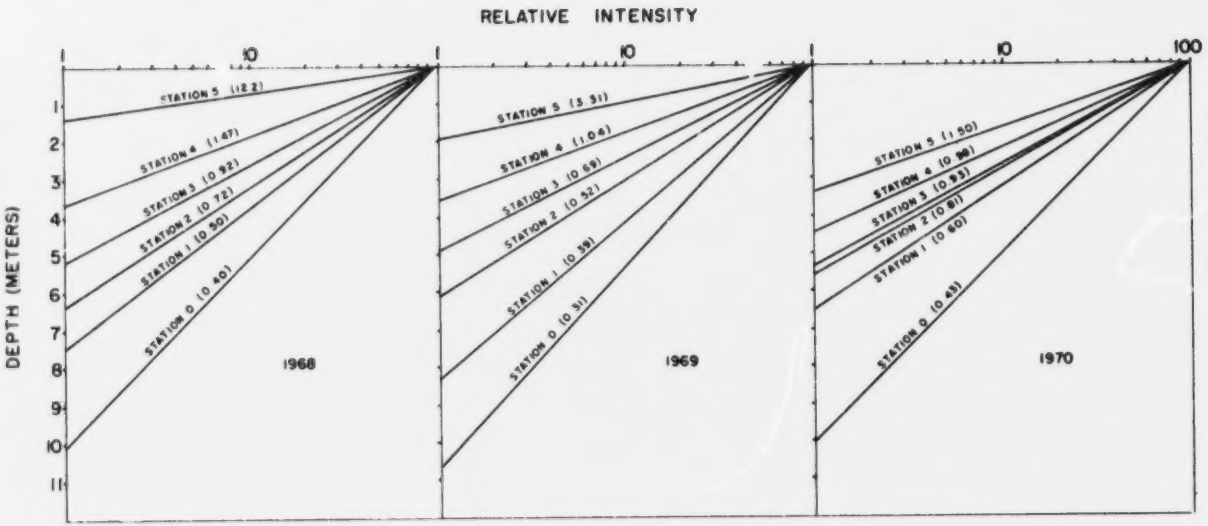

Figure 14. Penetration of total visible light and average extinction coefficients (k/m) for each sampling station during 1968, 1969 and 1970, Bighorn Lake.

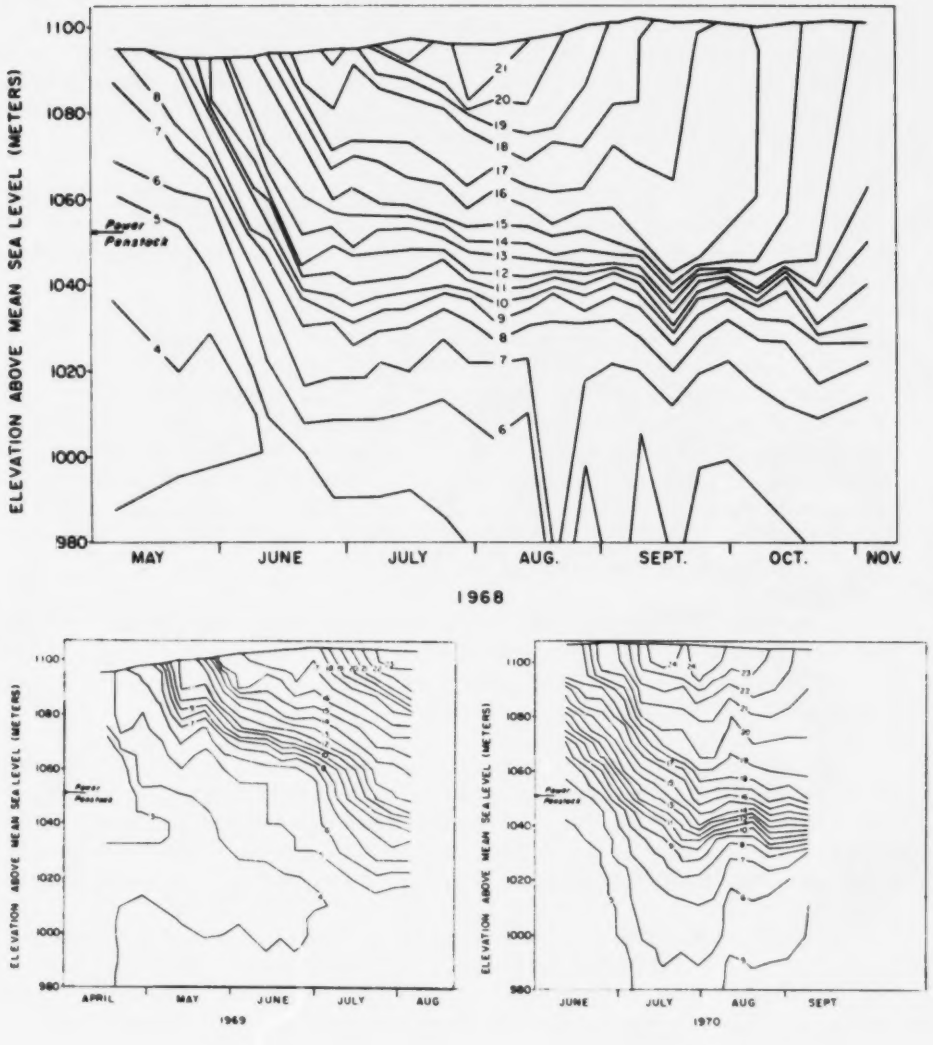

Figure 15. Isotherms (C) at station 0 during 1968, 1969 and 1970, Bighorn Lake.

with the bottom of the reservoir. Warmer water was also found on the bottom of the reservoir from the latter part of April to the end of June in 1969.

A rapid spring warming of the reservoir was evident for all three years. During 1968 this process occurred until 27 June, after which the isotherms were horizontal and there was a temperature difference of 14.4 C between the surface and the bottom. Although thermally stratified through November, a sharply defined thermocline was not evident. After 29 July, there was a gradual cooling of the upper portion of the reservoir and by 2 November thermal stratification was greatly weakened.

The degree of thermal stratification that occurred during 1970 was stronger than that of 1969. Again the development of a sharply defined thermocline for either of the above years was not evident.

A significant fact was the change of temperature at the depth of the power penstocks (1,051 meters). During 1968, from 5 May to 27 June the temperature increased at this depth from 4.4 to 13.0 C. A much slower increase of temperature followed reaching 16.8 on 7 September. After 7 September, temperature at the power penstock elevation decreased, attaining a value of 12.0 on 2 November. Similar trends in temperature fluctuations at the penstock elevation were observed for the 1969 and 1970 sampling periods, although they were not as well defined as in 1968.

Figure 15 also illustrates the fact that the greatest rate of temperature decline with depth was in the stratum of water immediately above and below the power penstock. For 1968 this occurred from 20 June through 10 September.

Longitudinal and seasonal changes in temperature for 1968 are portrayed in Figure 16. The warming process began in the upper end of Bighorn Lake and then advanced downstream and to greater depths during the summer. By 5 May, the 4.0 C isotherm had advanced to the dam and the 13.0 C isotherm was in the upper end of the reservoir.

By 7 June, the surface waters at station 3 had warmed to 18.0 C and the 4.0 C isotherm had almost disappeared. The cell of cold water at station 4 was attributed to run-off into the reservoir from a small, snow-fed tributary in that area.

On 8 July, the entire surface was at or above 20.0 C and the 22.0 C isotherm had started to develop in the upper end. By 3 September, a rather distinct stratification developed between elevations 1,060 and 1,035.

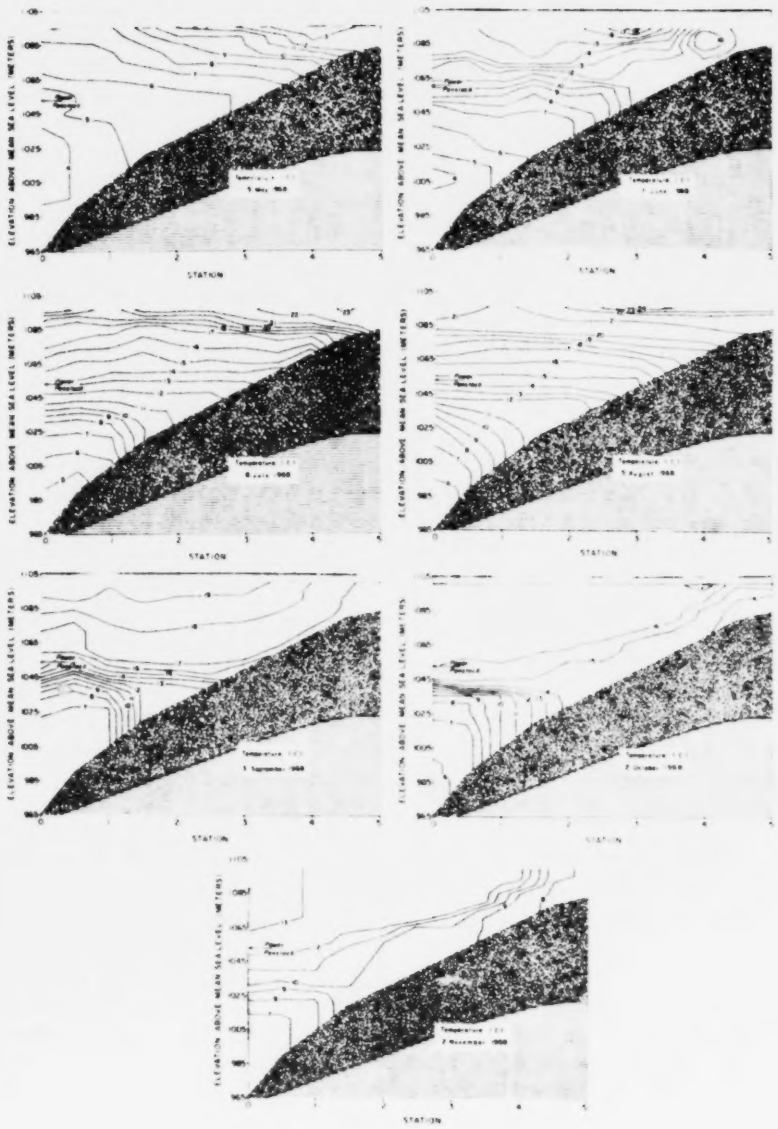

Figure 16. Distribution of 1 C isotherms in Bighorn Lake during 1968.

By 2 October, the surface water was 17.0 C or lower and a 14.0 C isotherm had developed in the upper end. As of 2 November, no temperature greater than 14.0 C was evident.

The above discussion illustrates the effectiveness of Bighorn Lake as a heat trap. Because of deep water withdrawal, summer influent temperatures are consistently warmer than those of the effluent. Therefore, during the summer the reservoir stored advected heat in addition to heat absorbed from solar radiation.

Isolines of conductivity at station 0 are portrayed in Figure 17. On 5 May 1968, a slight degree of chemical stratification was evident ranging from 900 micromhos at the surface to 1,120 micromhos at the bottom. Above elevation 1,070 a marked change in conductivity occurred after 3 July as flood water flowing along the surface layers of the reservoir reached this station. A drop in conductivity from 850 to less than 650 micromhos occurred between 3 and 25 July. Water of conductivity between 650 and 600 micromhos persisted at the surface from 25 July to 27 September following which the conductivity increased to 760 micromhos on 2 November. This increase in conductivity was partly due to down-reservoir flow of higher conductive water associated with low flow conditions and partly due to mixing with the deeper water of higher conductivity as a result of the breakdown of thermal stratification.

The most striking aspect of the 1968 data was the tongue of water between elevation 1,070 and 1,035 exhibiting a conductivity minimum from 18 June to 7 September. The centerline through the tongue occurred at the depth of the power penstock. Wright (1969) showed that the position of the tongue of low conductive water was similar in position to a well defined density layer.

During 1969 and 1970 there appeared to be a progressive increase in conductivity from the surface to the bottom. Chemical stratification was observed for both years, but the development of low conductivity water masses at the power penstock elevation was less distinct.

Longitudinal and seasonal changes in conductance are presented in Figure 18. On 5 May 1968, water of conductivity less than 900 micromhos was overriding water of higher conductivity from stations 2 to 3. The downward bending of the 900 and 950 micromho isolines between stations 1 and 0, in contrast to the horizontal isoline of 1,000 micromhos, indicates that penstock withdrawal of water was occurring above elevation 1,032.

By 7 June, peak runoff had begun and water of conductivity ranging from less than 500 micromhos to 900 hicromhos had filled the upper

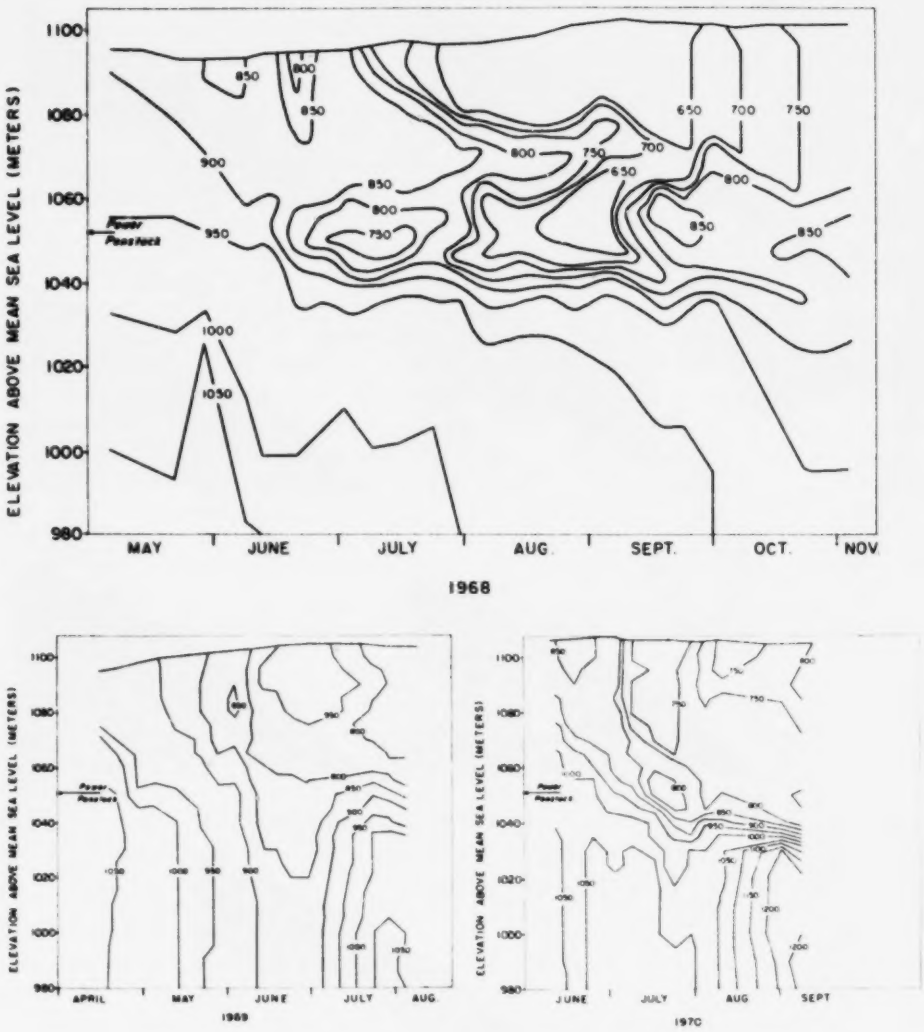

Figure 17. Isolines of conductivity (micromhos) at station 0 during 1968, 1969 and 1970, Bighorn Lake.

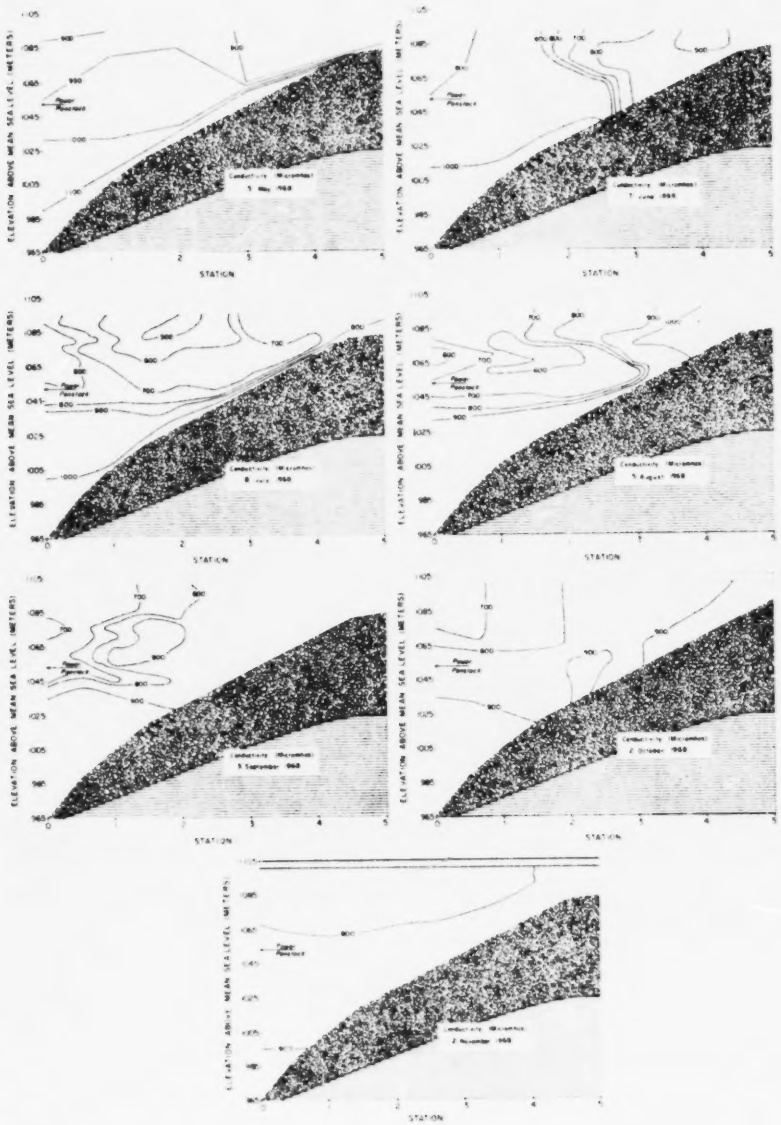

Figure 18. Distribution of 100 micromho isolines of conductivity in Bighorn Lake during 1968.

end of the reservoir. Water of conductance higher than 1,000 micromhos, that occupied the bottom at the upper end, had been displaced down-reservoir to almost station 2.

By 8 July, water having a conductivity above 800 micromhos had been split into two separate masses. One mass occurred as a discrete body between the dam and 9.6 km (6 mi) from the dam and above the power penstock elevation. The other mass occupied the lower portion of the reservoir below the power penstock elevation. By the above date large inflows had diminished and water of higher conductivity had entered the upper end of the reservoir displacing the 600 micromho water downstream by 32.2 km (20 mi).

On 5 August, it was evident that the water of greater conductance had been separated into two masses above and below the power penstock elevation. As a result of withdrawal and the influx of higher conductive water associated with low stream flow, water having a conductivity of less than 600 micromhos had been isolated at elevations 1,085 and 1,055 between stations 1 and 3.

By 2 October, the pattern described above had been eliminated and water of conductivity between 800 and 900 micromhos was being discharged. Influent water of higher conductance flowed along the bottom, instead of surface or sub-surface because of the cooler water temperatures at this time of year.

On 2 November, as a result of vertical mixing due to breakdown of thermal stratification, there had virtually been an elimination of vertical chemical stratification.

Water Chemistry

Concentrations of the major cations and anions found in Bighorn Lake are given in Table XIII. This table gives the range and mean of a given element for the complete strata of water sampled at the indicated sampling station for that year.

Calcium, magnesium, sodium and potassium. as well as bicarbonate, sulfate and chloride have previously been demonstrated to act in a relatively conservative manner (Table VIII). A comparison of the mean concentration of a given element at any station gives additional evidence to support this fact. In general, the vertical and horizontal distribution of each of the above constituents stayed relatively homogeneous as indicated by the similar seasonal averages for each station (Table XIII). Comparisons by means of a t-test for paired observations showed that there was no significant difference in the mean concentrations of these elements for any pair of stations during 1968 and 1969.

Table XIII. Range and mean water chemistry at each station of Bighorn Lake during the study.

	Station 0								
	1968			1969			1970		
	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum
Ca^{++} (meq/1)	9.05	4.38	2.74	4.64	4.08	3.12			
Mg^{++} (meq/1)	4.66	2.13	0.84	2.40	1.96	1.19			
Na^{+} (meq/1)	4.15	3.34	2.10	4.25	3.59	2.46			
K^{+} (meq/1)	0.15	0.11	0.03	0.15	0.12	.08			
HCO_3^{-} (meq/1)	4.53	3.21	2.00	3.80	3.27	2.55			
Cl^{-} (meq/1)	0.38	0.29	0.17	0.41	0.35	0.25			
$SO_4^{=}$ (meq/1)	8.35	5.74	2.67	7.25	5.66	3.92			
F^{-} (meq/1)	0.19	0.05	0.01	0.06	0.04	0.02			
NO_3^{-}-N (mg/1)	0.90	0.51	0.22	0.79	0.50	0.14	0.79	0.57	0.01
NO_2^{-}-N (mg/1)	0.035	0.006	0.000	0.013	0.004	0.001	0.059	0.005	0.000
NH_3-N (mg/1)	0.25	0.07	0.00	0.60	0.20	0.00	0.15	0.02	0.01
Ortho-$PO_4^{=}$ (mg/1)	0.80	0.08	0.00	0.15	0.04	0.00	0.14	0.05	0.00
Turbidity (J.T.U.)	22	11	4	12	8	4			
Silica (mg/1)	12.4	9.9	6.4	15.8	10.4	5.8			
Dissolved Oxygen (mg/1)	11.6	5.6	0.6	10.0	6.4	4.2	10.9	6.4	3.4
Conductance (micromhos)	1300	866	600	1064	918	685	1282	942	692
pH	8.77		7.55	8.70		7.53	8.80		7.50

Table XIII. (Cont'd)

	Station 1								
	1968			1969			1970		
	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum
Ca^{++} (meq/l)	8.26	3.99	2.55	4.49	3.86	2.99			
Mg^{++} (meq/l)	4.33	2.10	0.75	3.84	1.98	1.12			
Na^{++} (meq/l)	4.40	3.14	1.90	4.40	3.59	2.50			
K^{+} (meq/l)	0.27	0.11	0.07	0.13	0.11	0.08			
HCO_3^{-} (meq/l)	4.55	2.97	2.09	3.40	3.05	2.36			
Cl^{-} (meq/l)	0.37	0.26	0.17	0.41	0.33	0.22			
$SO_4^{=}$ (meq/l)	8.83	5.62	2.83	6.75	5.54	4.12			
F^{-} (meq/l)	0.18	0.05	0.00	0.06	0.04	0.03			
NO_3^{-}-N (mg/l)	0.89	0.52	0.11	0.76	0.49	0.23	0.74	0.56	0.08
NO_2^{-}-N (mg/l)	0.051	0.008	0.000	0.043	0.006	0.001	0.065	0.007	0.001
NH_3-N (mg/l)	0.00	0.08	0.33	0.46	0.21	0.01	0.08	0.03	0.01
Ortho-$PO_4^{\equiv}$ (mg/l)	0.63	0.08	0.00	0.10	0.04	0.00	0.14	0.07	0.00
Turbidity (J.T.U.)	44	17	8	12	8	4			
Silica (mg/l)	14.6	10.2	6.7	13.4	10.0	5.4			
Dissolved Oxygen (mg/l)	10.7	6.2	1.4	10.8	7.3	4.7	9.1	6.0	3.6
Conductance (micromhos)	1000	798	540	1050	880	590	1077	916	566
pH	8.78		7.65	8.63		7.90	8.65		7.00

Table XIII. (Cont'd)

	Station 2								
	1968			1969			1970		
	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum
Ca^{++} (meq/1)	7.28	4.00	2.18	5.76	3.87	2.92			
Mg^{++} (meq/1)	3.81	1.99	0.81	2.44	1.79	1.08			
Na^{++} (meq/1)	4.65	3.18	1.50	4.65	3.69	2.40			
K^{+} (meq/1)	0.18	0.12	0.06	0.13	0.11	0.08			
HCO_3^{-} (meq/1)	3.52	2.93	1.29	3.50	2.92	2.22			
Cl^{-} (meq/1)	0.36	0.25	0.13	0.44	0.32	0.18			
$SO_4^{=}$ (meq/1)	8.64	5.50	3.00	7.21	5.52	3.12			
F^{-} (meq/1)	0.16	0.05	0.00	0.08	0.04	0.03			
NO_3^{-}-N (mg/1)	0.95	0.52	0.11	0.15	0.49	0.12	0.88	0.53	0.05
NO_2^{-}-N (mg/1)	0.038	0.009	0.000	0.019	0.006	0.001	0.039	0.009	0.001
NH_3-N (mg/1)	0.31	0.08	0.00	0.31	0.25	0.00	0.07	0.03	0.01
Ortho-$PO_4^{=}$ (mg/1)	0.85	0.15	0.00	0.13	0.05	0.00	0.30	0.09	0.00
Turbidity (J.T.U.)	68	24	4	16	10	4			
Silica (mg/1)	14.7	10.6	7.3	14.6	10.2	6.7			
Dissolved Oxygen (mg/1)	11.2	6.8	2.5	11.1	7.3	4.1	9.8	5.1	0.5
Conductance (micromhos)	1370	816	430	1298	869	531	526	799	1092
pH	8.74		7.61	8.70		7.61	8.65		7.00

Table XIII. (Cont'd)

	Station 3								
	1968			1969			1970		
	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum
Ca^{++} (meq/1)	8.83	4.11	2.74	4.24	3.73	3.13			
Mg^{++} (meq/1)	2.32	2.01	0.92	2.32	1.76	0.92			
Na^{+} (meq/1)	4.25	3.11	1.95	4.78	3.63	2.50			
K^{+} (meq/1)	0.18	0.12	0.08	0.13	0.11	0.07			
HCO_3^{-} (meq/1)	3.49	2.86	2.08	3.45	2.84	2.32			
Cl^{-} (meq/1)	0.33	0.24	0.14	0.40	0.31	0.20			
$SO_4^{=}$ (meq/1)	7.94	5.57	2.65	6.89	5.46	3.62			
F^{-} (meq/1)	0.15	0.06	0.01	0.06	0.04	0.02			
NO_3^{-}-N (mg/1)	0.83	0.49	0.10	1.46	0.52	0.21	0.80	0.51	0.08
NO_2^{-}-N (mg/1)	0.033	0.011	0.001	0.043	0.011	0.003	0.065	0.012	0.003
NH_3-N (mg/1)	0.66	0.08	0.00	0.44	0.25	0.13	0.44	0.04	0.01
Ortho-$PO_4^{=}$ (mg/1)	0.78	0.10	0.00	0.18	0.07	0.00	0.77	0.11	0.00
Turbidity (J.T.U.)	217	49	4	34	18	6			
Silica (mg/1)	17.6	10.5	7.6	12.4	10.2	8.3			
Dissolved Oxygen (mg/1)	10.0	7.3	3.1	9.9	7.4	5.2	10.3	5.0	0.5
Conductance (micromhos)	1320	828	450	1628	843	531	1105	729	143
pH	8.75		7.40	8.56		7.91	8.80		7.05

Table XIII. (Cont'd)

	Station 4								
	1968			1969			1970		
	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum
Ca^{++} (meq/l)	8.92	4.38	2.92	4.16	3.64	2.96			
Mg^{++} (meq/l)	4.82	1.96	0.19	2.40	1.64	0.84			
Na^{+} (meq/l)	4.30	3.24	0.90	4.95	3.59	2.90			
K^{+} (meq/l)	0.14	0.12	0.06	0.14	0.11	0.08			
HCO_3^{-} (meq/l)	3.54	3.02	2.12	3.55	2.82	2.39			
Cl^{-} (meq/l)	0.34	0.24	0.07	0.44	0.34	0.16			
$SO_4^{=}$ (meq/l)	7.87	5.63	2.75	7.37	5.57	3.02			
F^{-} (meq/l)	0.14	0.04	0.00	0.07	0.04	0.03			
NO_3^{-}-N (mg/l)	0.66	0.44	0.09	0.72	0.47	0.29	0.74	0.44	0.10
NO_2^{-}-N (mg/l)	0.029	0.009	0.001	0.018	0.013	0.004	0.046	0.019	0.005
NH_3-N (mg/l)	0.76	0.12	0.00	0.53	0.35	0.18	0.39	0.05	0.03
Ortho-$PO_4^{=}$ (mg/l)	1.00	0.11	0.00	0.21	0.10	0.00	0.25	0.11	0.00
Turbidity (J.T.U.)	350	67	12	83	40	16			
Silica (mg/l)	13.9	10.7	8.2	12.8	10.6	9.0			
Dissolved Oxygen (mg/l)	9.6	7.9	5.4	10.7	7.7	6.0	11.8	5.8	2.9
Conductance (micromhos)	1300	858	405	1369	818	407	1199	711	511
pH	8.80		7.57	8.58		7.90	8.75		7.00

Table XIII.(Cont'd)

	Station 5								
	1968			1969			1970		
	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum
Ca^{++} (meq/1)	8.96	4.62	3.48	4.01	3.66	3.18			
Mg^{++} (meq/1)	4.75	2.13	0.52	2.00	1.56	1.31			
Na^{+} (meq/1)	4.55	3.50	1.97	5.05	3.42	2.11			
K^{+} (meq/1)	0.18	0.13	0.11	0.13	0.11	0.08			
HCO_3^{-} (meq/1)	3.38	3.10	2.16	3.00	2.77	2.41			
Cl^{-} (meq/1)	0.35	0.27	0.14	0.39	0.30	0.25			
$SO_4^{=}$ (meq/1)	7.54	6.39	3.54	6.25	5.42	4.25			
F^{-} (meq/1)	0.17	0.06	0.00	0.06	0.04	0.03			
NO_3^{-}-N (mg/1)	0.73	0.44	0.13	0.89	0.44	0.02	0.72	0.50	0.09
NO_2^{-}-N (mg/1)	0.030	0.011	0.004	0.023	0.011	0.010	0.029	0.019	0.007
NH_3-N (mg/1)	0.22	0.06	0.00	0.49	0.42	0.31	0.12	0.04	0.01
Ortho-$PO_4^{=}$ (mg/1)	0.72	0.18	0.00	0.24	0.16	0.16	0.30	0.11	0.00
Turbidity (J.T.U.)	3350	558	44	875	211	36			
Silica (mg/1)	12.9	11.4	9.8	14.4	11.2	9.2			
Dissolved Oxygen (mg/1)	12.6	8.3	6.2	13.0	9.3	6.4	12.1	6.7	3.7
Conductance (micromhos)	1070	882	460	1133	833	697	1008	731	500
pH	8.72		8.10	8.71		8.31	8.90		7.55

Concentrations of nitrogen, phosphate, silica, dissolved oxygen and hydrogen ion are highly non-conservative and rather large fluctuations in the concentration of these elements were often observed (Table XIII). Silica was never recorded less than 5.4 mg/l, which is well above the minimum requirements for most diatoms (Lund, 1954; 1964).

The greatest vertical range of dissolved oxygen was from 0.6 to 11.6 mg/l at station 0. The lower oxygen values were observed in the hypolimnetic waters during summer stagnation, while the higher values were usually associated with periods of large phytoplankton standing crop.

The mean concentrations of certain elements occurring in the euphotic zone are presented in Table XIV. Total inorganic nitrogen (primarily nitrate nitrogen), ortho-phosphate, iron, manganese and zinc were usually in higher concentrations at station 5 than any other station; but no significant differences in concentration were found between stations 0, 1 and 2. These higher concentrations were attributed to the larger amount of suspended sediment at station 5 carried into the reservoir by the Bighorn and Shoshone Rivers.

Euphotic zone pH ranged from 7.60 to 8.88 during the study. The majority of the higher pH values occurred during the summer.

In relation to average natural waters, the content of total inorganic nitrogen and inorganic phosphate in Bighorn Lake is relatively high. Mackenthun (1965) showed that nuisance blooms of algae may be expected when inorganic phosphate and nitrogen reach average concentrations exceeding 0.01 mg/l and 0.30 mg/l, respectively. The above levels were usually exceeded in Bighorn Lake.

The complex interaction of thermal stratification, density flow and seasonal inflow and outflow not only exhibited an effect on the distribution of conductivity, but also altered the depth distribution of nitrate, ortho-phosphate, dissolved oxygen, pH and turbidity concentrations during 1968. The distribution of turbidity with depth at station 0 is portrayed in Figure 19. From the end of June through the middle of October there was a turbidity maximum present at the power penstock elevation. This turbidity maximum was associated with water of minimum conductivity characteristic of the high flow conditions in June. Apparently a current was established that was strong enough to retain some of the suspended silt that entered the reservoir in June.

There was also an ortho-phosphate maximum (Fig. 20) present during August of 1968 at the penstock elevation. This sub-surface maximum of phosphate was attributed to the phosphate being associated with the sediment washed into the reservoir by the heavy run-off in

Table XIV. Mean water chemistry (mg/l) of the euphotic zone at each station of Bighorn Lake during the study.

	Station					
1968	0	1	2	3	4	5
pH Range	7.80-8.69	8.02-8.75	8.01-8.78	8.16-8.81	8.00-8.70	8.00-8.72
NO_3^--N	0.35	0.30	0.37	0.40	0.50	0.59
NO_2^--N	0.009	0.007	0.008	0.012	0.011	0.014
NH_3-N	0.09	0.08	0.09	0.09	0.12	0.16
Ortho-$PO_4^{\equiv}$	0.08	0.07	0.08	0.13	0.09	0.15
1969	0	1	2	3	4	5
pH Range	8.03-8.70	8.05-8.73	8.15-8.86	8.23-8.88	8.17-8.75	8.17-8.79
NO_3^--N	0.40	0.38	0.32	0.35	0.39	0.49
NO_2^--N	0.008	0.008	0.007	0.008	0.007	0.009
NH_3-N	0.19	0.20	0.19	0.20	0.25	0.34
Ortho-$PO_4^{\equiv}$	0.06	0.04	0.04	0.07	0.04	0.09
Total Iron	0.030	0.030	0.038	0.050	0.086	0.135
Mn^{++}	0.013	0.014	0.013	0.007	0.015	0.036
Cu^{++}	0.001	0.001	0.001	0.001	0.001	0.001
Zn^{++}	0.011	0.010	0.008	0.009	0.009	0.020
1970	0	1	2	3	4	5
pH Range	8.00-8.70	8.15-8.60	7.60-8.65	7.90-8.80	7.85-8.50	7.55-8.75
NO_3^--N	0.34	0.30	0.28	0.25	0.30	0.44
NO_2^--N	0.010	0.011	0.010	0.010	0.014	0.018
NH_3-N	0.02	0.03	0.03	0.04	0.04	0.05
Ortho-$PO_4^{\equiv}$	0.03	0.06	0.07	0.08	0.10	0.10

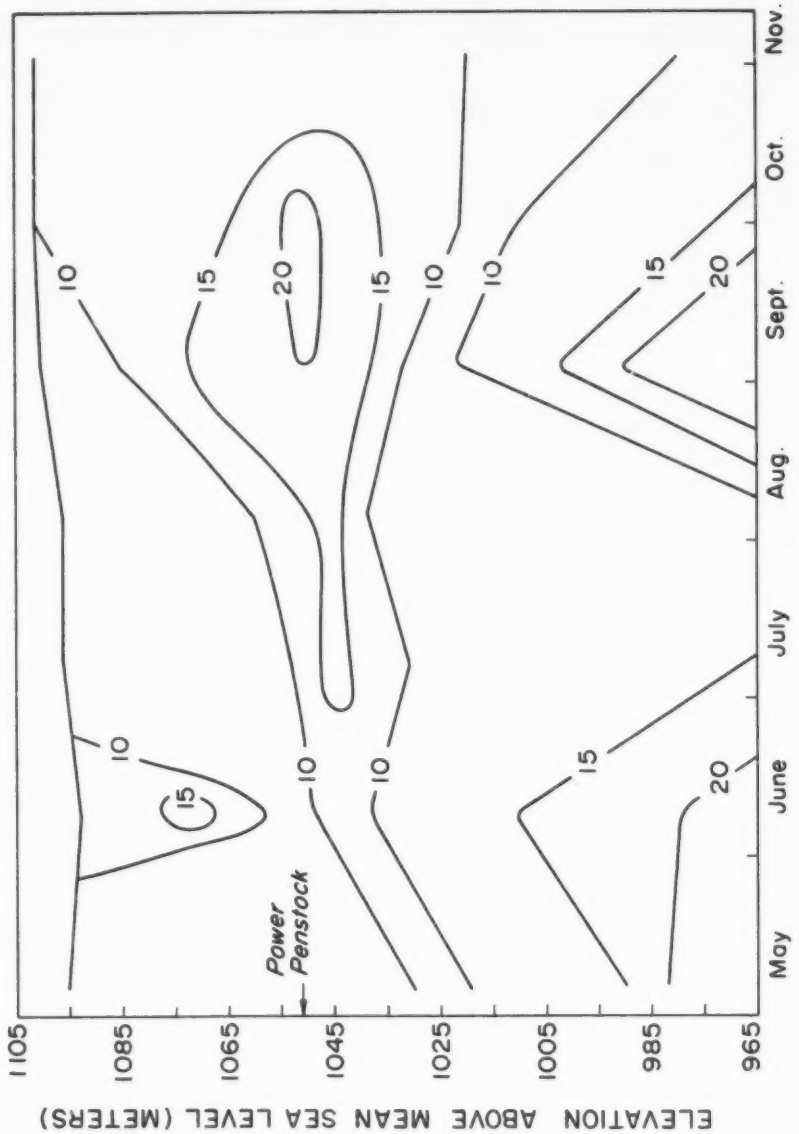

Figure 19. Distribution of turbidity (Standard Jackson Turbidity Units) with depth at station 0 of Bighorn Lake during 1968.

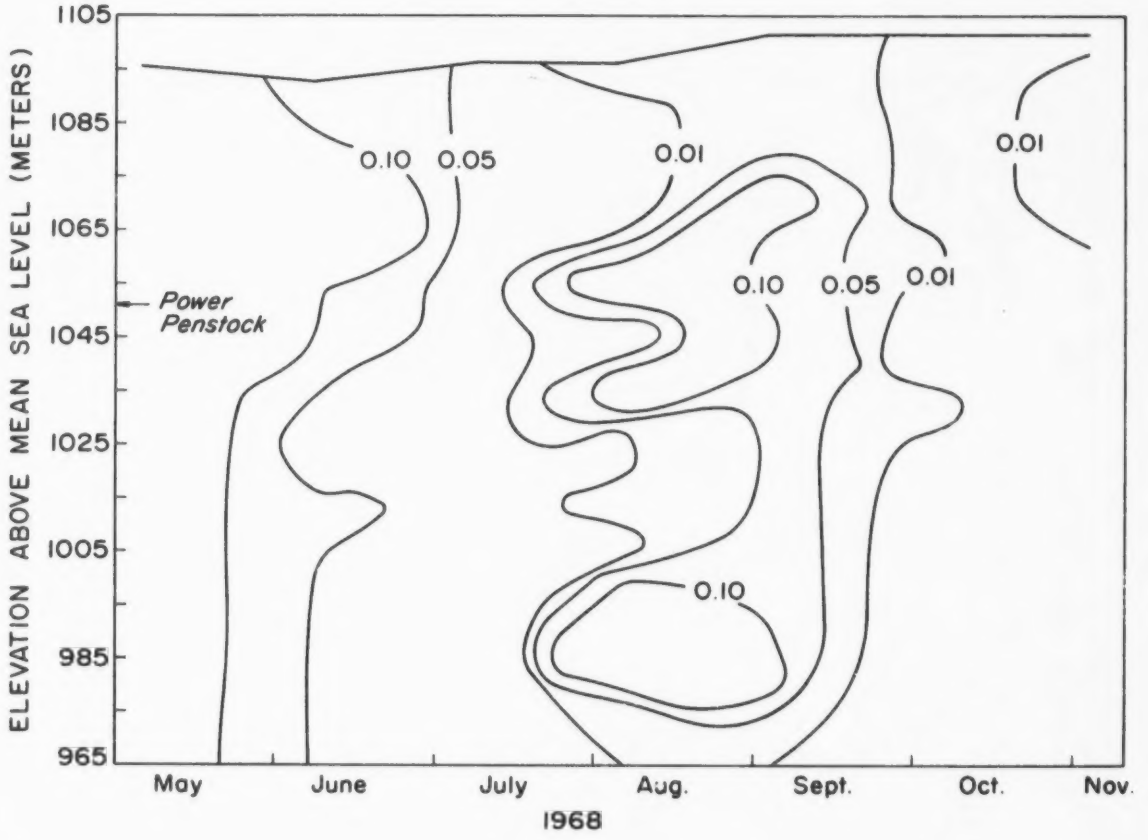

Figure 20. Distribution of ortho-phosphate (mg/l $PO_4^{\equiv}$) with depth at station 0 of Bighorn Lake during 1968.

June. Being below the euphotic zone it was not utilized by phytoplankton and thus was discharged through the penstock. It will be noted that there was phosphate depletion in the surface layers of the reservoir from May to August. Slightly increased values of phosphate in surface waters during August and September were also associated with low conductivity water that originated from high flow conditions again in June.

A similar pattern is shown in nitrate (Fig. 21) with a tongue of high nitrate nitrogen water at the power penstock elevation from June to September. From September to November water of lower nitrate content was at this elevation. In contrast to phosphate, there was no decline in nitrate in the euphotic zone; instead, the concentrations increased during September and October.

Figure 22 presents data for oxygen and Figure 23 for pH. It is evident that a layer of water with minimum oxygen and pH was at the power penstock elevation. The low oxygen and hydrogen ion concentrations were probably due to respiratory processes. However, it does not seem possible that respiration in situ was responsible for the decreased oxygen and pH values as the water mass moved downstream away from the bottom. It will be noted that the oxygen and pH values both are similar to those of the stagnant bottom water at station 0. This suggests that oxygen depletion and carbon dioxide increase occurred while the water was on the bottom of the reservoir upstream from station 0 and the water mass preserved these characteristics as it moved down the reservoir toward the power penstock.

If a line perpendicular to the dam (parellel to the water's surface) is drawn from the power penstock elevation upstream from the dam, this line would intersect the bottom of the reservoir approximately 48.3 km (30 mi) from the dam.

Phytoplankton Standing Crop and Chlorophyll

Table XV lists all the phytoplankton taxa identified from the composited euphotic zone samples. This list of the Bighorn Lake flora contains 51 genera and 58 species of algae.

It is important to remember that from year to year the early and late sampling periods do not coincide and there may exist a built-in bias in the presentation of the phytoplankton data.

The Bacillariophyceae were the dominant class of phytoplankton comprising 58.8, 71.5 and 42.9% of the total cell volume during 1968, 1969 and 1970, respectively. Fragilaria crotonensis was the most important organism of the phytoplankton on a cell volume basis (Table XVI), but ranked fourth according to presence (Table XVII).

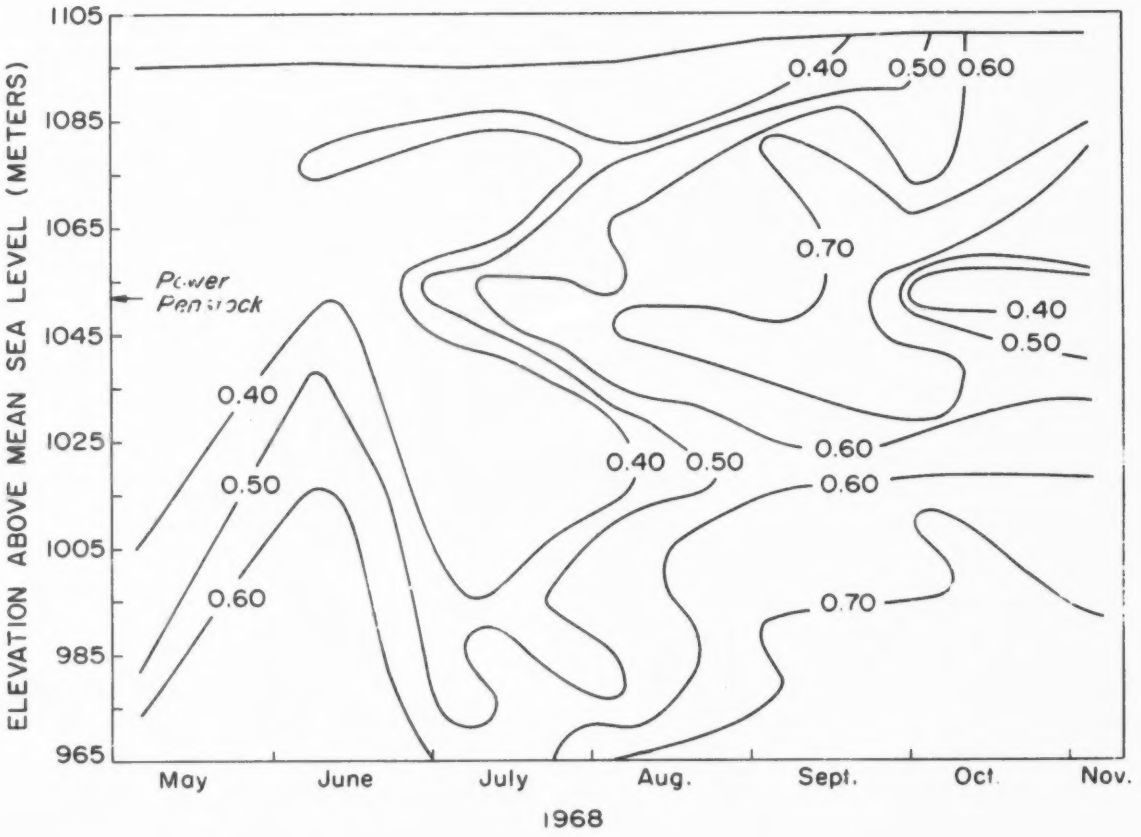

Figure 21. Distribution of nitrate nitrogen (mg/l NO_3^--N) with depth at station 0 of Bighorn Lake during 1968.

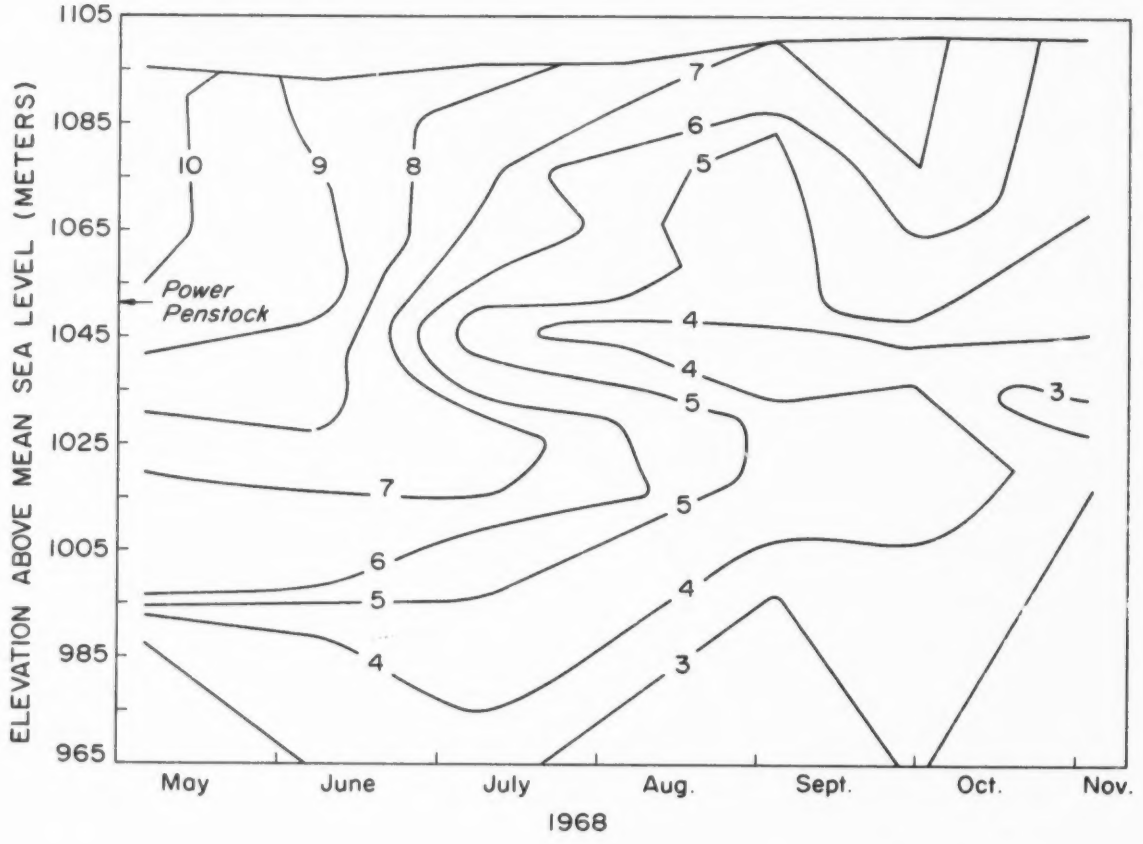

Figure 22. Distribution of dissolved oxygen (mg/l) with depth at station 0 of Bighorn Lake during 1968.

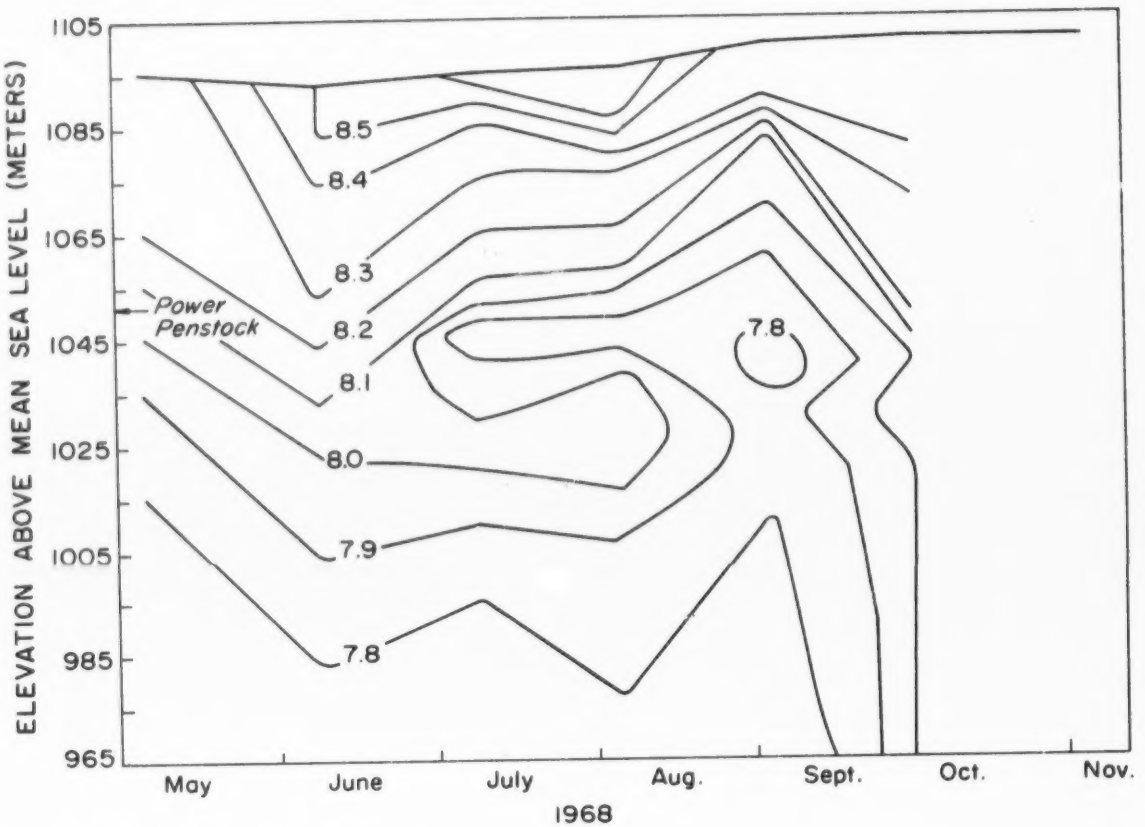

Figure 23. Distribution of pH with depth at station 0 of Bighorn Lake during 1968.

Table XV. Phytoplankton species observed from all sampling stations of Bighorn Lake during the study with some calculated volumes of individual cells or colonies.

	μ^3
DIVISION CHLOROPHYTA (Green Algae)	
Class Chlorophyceae	
Actinastrum Hantzschii Lagerheim.	213
Arkistrodesmus Braunii (Naeg.) Brunnthaler.	200
Arkistrodesmus falcatus (Corda) Ralfs.	35
Carteria sp. Diesing.	68
Characium sp. A. Braun.	252
Chlamydomonas sp. Ehr.	41
Chlorella spp. Beijernick.	
Closterium sp. Nitzsch.	2,312
Cosmarium subcostatum Nordstedt.	
Crucigenia sp. Morren.	34
Pandorina morum Bory.	132
Pediastrum duplex Meyen. (Col.)	44,792
Oocystis sp. Naegeli.	403
Scenedesmus acuminatis (Lag.) Chodat.	362
Scenedesmus quadricauda (Turp.) deBrebisson.	152
Schroederia setigera (Schroed.) Lemmermann.	321
Staurastrum paradoxum Meyen.	11,521
Stichococcus bacillaris Nägeli.	31
Tetraëdron sp. Kütz.	
Westella botryoides (W.West) deWildemann.	
Westella linearis Cr. M. Smith.	
DIVISION CRYSOPHYTA (Yellow-green Algae)	
Class Bacillariophyceae (Diatoms)	
Achnanthes lanceolata Breb.	171
Asterionella formosa Hassall.	761
Caloneis amphisbaena (Bory) Cleve.	23,024
Cocconeis spp. Ehr.	
Cyclotella spp. Kütz.	
Cymbella affinis Kütz.	3,717
Diatoma elongatum Agardh.	875
Diatoma hiemale (Lyngbye) Heiberg.	2,985
Diatoma vulgare Bory.	974

Table XV. (Cont'd)

	μ^3
Diatomella Balfouriana Greville.	1,006
Eunotia sp. Ehr.	295
Fragilaria capucina Desmazieres.	385
Fragilaria crotonensis Kitton.	1,057
Gomphonema spp. Agardh.	
Gyrosigma Spencerii (W. Smith) Cleve.	16,896
Hannaea arcus (Ehr.) Patr.	1,414
Melosira granulata (Ehr.) Ralfs	492
Melosira italica (Ehr.) Kütz.	520
Navicula spp. Bory.	
Nitzschia spp. Hassall.	
Stephanodiscus niagarae Ehr.	41,700
Surirella ovata Kütz.	7,120
Synedra ulna (Nitzsch) Ehr.	9,567
Class Chrysophyceae	
Chrysococcus sp. Klebs.	25
Dinobryon sertularia Ehr.	1,236
Class Xanthophyceae (Heterokontae)	
Botryococcus sudeticus Lemmermann.	263
DIVISION CYANOPHYTA (Blue-green Algae)	
Class Myxophyceae	
Anabaena sp. Bory. (1 mm)	12,570
Aphanizomenon flos-aquae (L.) Ralfs. (1 mm)	12,570
Coelosphaerium Nageliarum Unger. (col.)	177,500
Coccochloris peniocystis Sprengel.	11
Merismopedia punctata Meyen.	
Microcystis aeruginosa Kuetz. (col.)	25,695
DIVISION PYRRHOPHYTA (Dinoflagellates)	
Class Dinophyceae (Dinokontae)	
Ceratium hirundinella (O.F.M.) Schrank.	108,307
Peridinium sp. Ehr.	2,340
DIVISION CRYPTOPHYTA (Blue and Red Flagellates)	
Class Cryptophyceae	
Cryptomonas ovata Ehr.	2,473
Rhodomonas lacustris Pasch. & Ruttn.	65

Table XVI. Rank of the major phytoplankton species from Bighorn Lake according to absolute mean cell volumes (mm^3/l) based on collections from all stations during the study.

Rank	Taxon	Cell Volume
1	Fragilaria crotonensis	1.222
2	Cryptomonas ovata	0.658
3	Stephanodiscus niagarae	0.518
4	Asterionella formosa	0.513
5	Aphanizomenon flos-aquae	0.487
6	Melosira granulata	0.173
7	Cyclotella spp.	0.165
8	Pediastrum duplex	0.143
9	Rhodomonas lacustris	0.105
10	Ceratium hirundinella	0.088
11	Navicula spp.	0.087
	Microcystis aeruginosa	0.087
12	Melosira italica	0.073
13	Diatoma vulgare	0.060
14	Synedra ulna	0.052

Table XVII. Rank of the major phytoplankton species of Bighorn Lake according to presence (%) as described by Curtis (1959). Values are based upon collections from all stations over the entire study.

Rank	Taxon	Presence
1	Rhodomonas lacustris	85.4
2	Cryptomonas ovata	84.8
3	Asterionella formosa	53.9
4	Fragilaria crotonensis	52.7
5	Stephanodiscus niagarae	36.3
6	Cyclotella spp.	33.7
7	Navicula spp.	32.7
8	Ankistrodesmus falcatus	31.3
9	Aphanizomenon flos-aquae	30.9
10	Oöcystis spp.	26.8
11	Melosira italica	25.9
12	Scenedesmus quadricauda	25.7
13	Melosira granulata	23.5
14	Diatoma vulgare	20.6
15	Schroederia setigera	18.8
16	Pandorina morum	17.9
17	Scenedesmus acuminatis	15.5
18	Ankistrodesmus Braunii	14.6
19	Anabaena sp.	12.2
	Synedra ulna	12.2
20	Diatoma elongatum	10.7

Presence is the number of stands of occurrence of a species expressed as a percentage of the total number of stands examined. Throughout the study, Asterionella formosa contributed more to the total cell volume than either Stephanodiscus niagarae or Melosira granulata. In 1970, S. niagarae and M. granulata had similar total cell volumes, but in 1968 and 1969, S. niagarae contributed four times the volume that M. granulata did to the total standing crop. Diatoma vulgare, Navicula spp., Cyclotella spp. and Melosira italica at times contributed large cell volumes even though presence was low compared to the previously mentioned diatoms. Synedra ulna and Diatoma elongatum were encountered in the samples but contributed little to the cell volume.

The Chlorophyceae were not an important class on a cell volume basis as they only contributed 6.4, 4.2 and 7.5% of the total cell volume of phytoplankton for 1968, 1969 and 1970, respectively. The green algae were represented by many genera, none of which showed a dominance in cell volume except Pediastrum duplex, a large colonial form (Table XVI). Ankistrodesmus falcatus ranked the highest according to presence of the chlorophytes (Table XVIII), but contributed little to the cell volume. Oocystis sp., Scenedesmus quadricauda, Schroederia setigera, Pandorina morum, Scenedesmus acuminatis and Ankistrodesmus Braunii were also frequently encountered.

The class Myxophyceae comprised 13.3, 6.4 and 17.5% of the total cell volume in 1968, 1969 and 1970, respectively. The blue-greens appeared in July and were present the remainder of the sampling season. Aphanizomenon flos-aquae was the most important representative of this class on a presence and cell volume basis. Other important members of this group were Anabaena sp. according to presence and Microcystis aeruginosa according to cell volume.

The dinoflagellates, Dinophyceae, were represented by Ceratium hirundinella and Peridinium sp., but C. hirundinella distinctly dominated this class on a cell volume basis (Table XVI).

Of the Cryptophyceae, Rhodomonas lacustris was the more frequently occurring phytoplankter (Table XVII). However, Cryptomonas ovata contributed most of the cell volume of this class as can be seen from Table XVI. The Cryptophyceae comprised 14.4, 14.9 and 28.6% of total cell volume in 1968, 1969 and 1970, respectively.

Chrysococcus sp. and Dinobryon sertularia, the only representatives of the Chrysophyceae, appeared in trace amounts as did Botryococcus sudeticus, the only representative of the Xanthophyceae.

The longitudinal phytoplankton distributions during the study are portrayed in Figure 24. The total standing crops of Chlorella sp.,

Table XVIII. Mean total phytoplankton standing crop ($X10^3$ mm^3/m^2) and chlorophyll *a* concentrations (mg/m^2) at each station during the study.

	Station					
1968	0	1	2	3	4	5
Standing Crop	13.55	20.46	21.46	24.40	15.19	4.82
Chlorophyll *a*	31.0	34.9	42.8	37.9	38.3	13.5
1969	0	1	2	3	4	5
Standing Crop	32.73	39.59	32.60	42.61	25.93	16.90
Chlorophyll *a*	30.4	30.5	43.3	41.8	42.1	25.4
1970	0	1	2	3	4	5
Standing Crop	31.65	56.37	39.90	37.15	26.54	22.39
Chlorophyll *a*	34.5	40.7	56.1	60.0	59.7	43.2

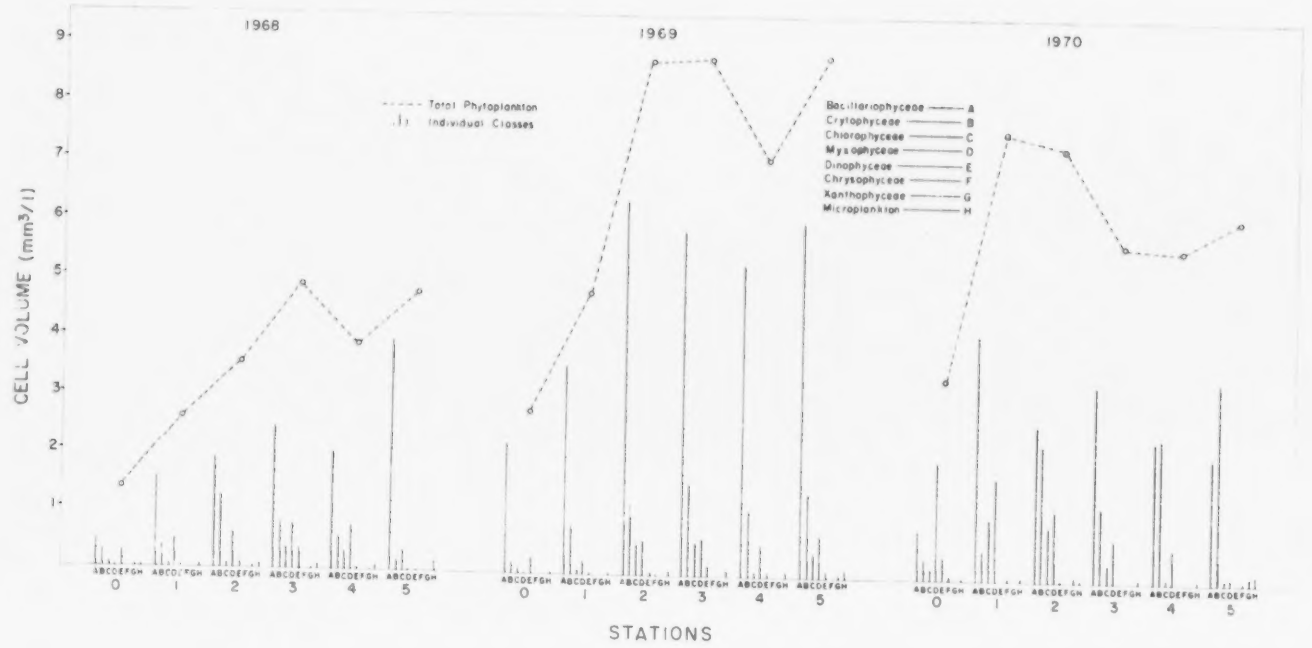

Figure 24. Yearly mean cell volumes (mm^3/l) of the phytoplankton at each station of Bighorn Lake during 1968, 1969 and 1970.

Tetraëdron sp., Chlamydomonas sp., Stichococcus bacillaris, Carteria sp., Coccochloris peniocystis, Merismopedia punctata and Chrysococcus sp. appear under the title of "Microplankton". This consolidation was necessary because distortion of cells, caused by preservation, made positive identification impossible much of the time and many of the above taxa were only encountered in a few samples.

In general, phytoplankton cell volumes increased from the dam to the upper end of Bighorn Lake and larger standing crops were observed in 1970 than in 1968 (Fig. 24).

The 1968 distribution of phytoplankton was represented by relatively small cell volumes at stations 0, 1 and 2 while stations 3, 4 and 5 were higher and had annual means of 4.90, 3.65 and 4.80 mm^3/l, respectively. The progressive increase in cell volume from stations 0 and 3 is evident with station 0 having an annual mean cell volume of 1.33 mm^3/l (Fig. 24).

The longitudinal distribution pattern of phytoplankton in 1969 was similar to that of 1968. The progressive increase in cell volume from station 0 to station 3 was again evident, but station 2 was almost equal in cell volume to station 3. Stations 2, 3, 4 and 5 all had cell volumes between 7.10 and 8.80 mm^3/l whereas station 0 had an annual mean cell volume of 2.79 mm^3/l.

In 1970, the cell volumes were higher at stations 1 and 2 with volumes of 7.65 and 7.40 mm^3/l respectively whereas station 0 exhibited the lowest volume of 3.48 mm^3/l (Fig. 24).

It is also apparent from Figure 24 that the Bacillariophyceae were the major contributors to the estimated cell volumes at each station during the study. However, in 1970 the Cryptophyceae were of equal or of greater importance in their contribution to the cell volumes at stations 4 and 5. The Myxophyceae are another class of organisms that accounted for substantial volumes at stations 2, 3 and 4 during 1968 and 1969, and stations 0, 1 and 2 during 1970.

Matched t-tests at the 95% confidence level demonstrated that there was a significant difference in the amount of phytoplankton at any particular station versus the phytoplankton volume at any adjacent station, except for stations 2 and 3 for 1969, and stations 3 and 4 for 1970. A significant difference in the mean phytoplankton volumes was found between all years except for 1969 and 1970.

The seasonal distribution of the monthly mean phytoplankton standing crops is depicted in Figure 25. Again the progressive increase in cell volumes from 1968 to 1970 was evident. Overall, the larger standing crops on a volume basis were observed in the earlier part of the sampling season.

In 1968, the phytoplankton reached the seasonal peak in July with Fragilaria crotonensis accounting for 26.8% by volume of the total cell volume during this month. Stations 1 and 2 exhibited the highest mean cell volumes of 2.96 and 3.67 $mm^3/1$, respectively. As the season progressed the amount of phytoplankton diminished to 1.05 $mm^3/1$, with the Bacillariophyceae becoming minimal in September corresponding to a maximum in the Myxophyceae. The Cryptophyceae and Dinophyceae both reached maxima in June and July.

It should be noted that the cell volumes of the Dinophyceae may be misrepresented. Ceratium hirundinella contributed primarily to this class and accurate volume determinations are difficult because of its large and irregular shape.

The amount of phytoplankton in April of 1969 was the recorded low (5.82 $mm^3/1$) for the season but increased to the seasonal peak of 7.65 $mm^3/1$ in May (Fig. 25). Asterionella formosa dominated the plankton during this peak. From May, the phytoplankton decreased and then increased to a second peak in July when Fragilaria crotonensis, Melosira granulata and Stephanodiscus niagarae were dominant. The Bacillariophyceae were maximal in May, then progressively decreased through the season as the Myxophyceae reached peak volumes in August.

The monthly mean cell volume in June of 1970 was 4.95 $mm^3/1$ and followed by an increase to the seasonal high of 8.45 $mm^3/1$ in August. June to August was dominated by the Bacillariophyceae and Cryptophyceae. The Myxophyceae were at a maximum in August (2.28 $mm^3/1$) then decreased to 1.63 $mm^3/1$ in September.

The phytoplankton successions observed during the course of the study are presented in Figures 26, 27 and 28. The indicated organisms comprised 64.1, 85.3 and 84.6% of the total cell volume during 1968, 1969 and 1970, respectively. Species succession was similar for all three years with a larger part of the standing crop made up of diatoms found in the spring and early summer. The latter was somewhat followed by the flagellates, Cryptomonas ovata and Rhodomonas lacustris. The flagellates were succeeded by the blue-greens, with Aphanizomenon flos-aquae reaching "bloom" proportions in September. Another diatom maximum in the fall was less distinct.

In summary, conditions of phytoplankton standing crop and species succession were similar for all years. The same species shown in Figures 26, 27 and 28 became dominant and declined as demonstrated by the above figures. Minor variations were found with respect to the dates and absolute values of standing crop attained.

As previously shown (Fig. 24), phytoplankton standing crop expressed on a volume basis ($mm^3/1$), decreased downstream from station

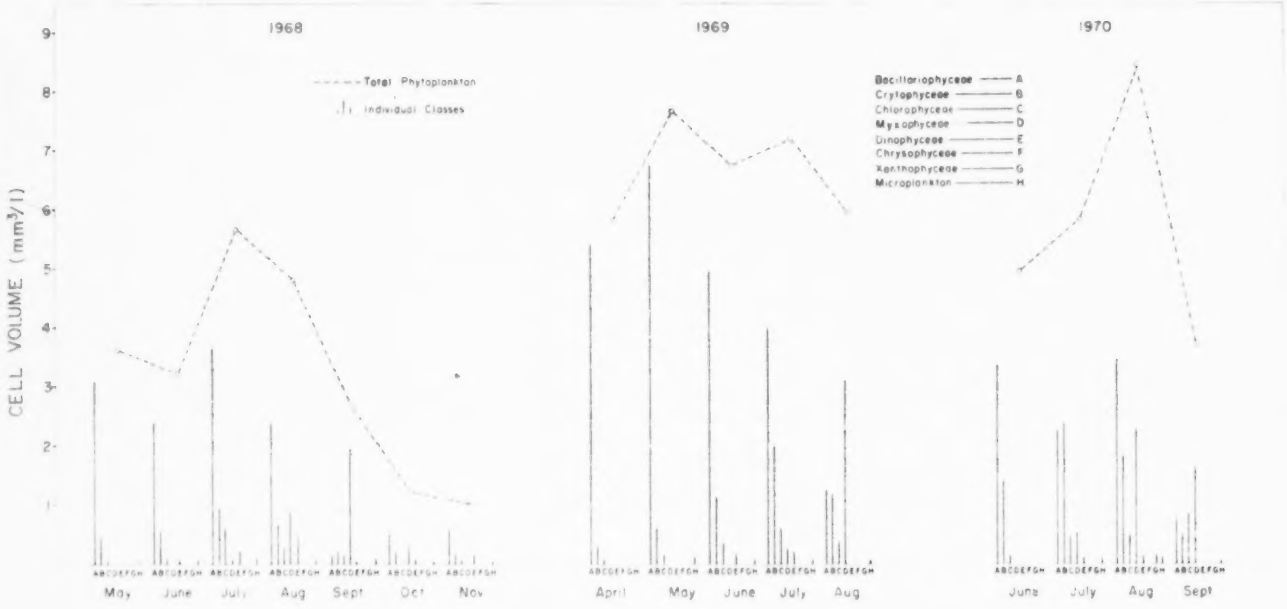

Figure 25. Monthly mean cell volumes (mm^3/l) of the phytoplankton in Bighorn Lake during 1968, 1969 and 1970.

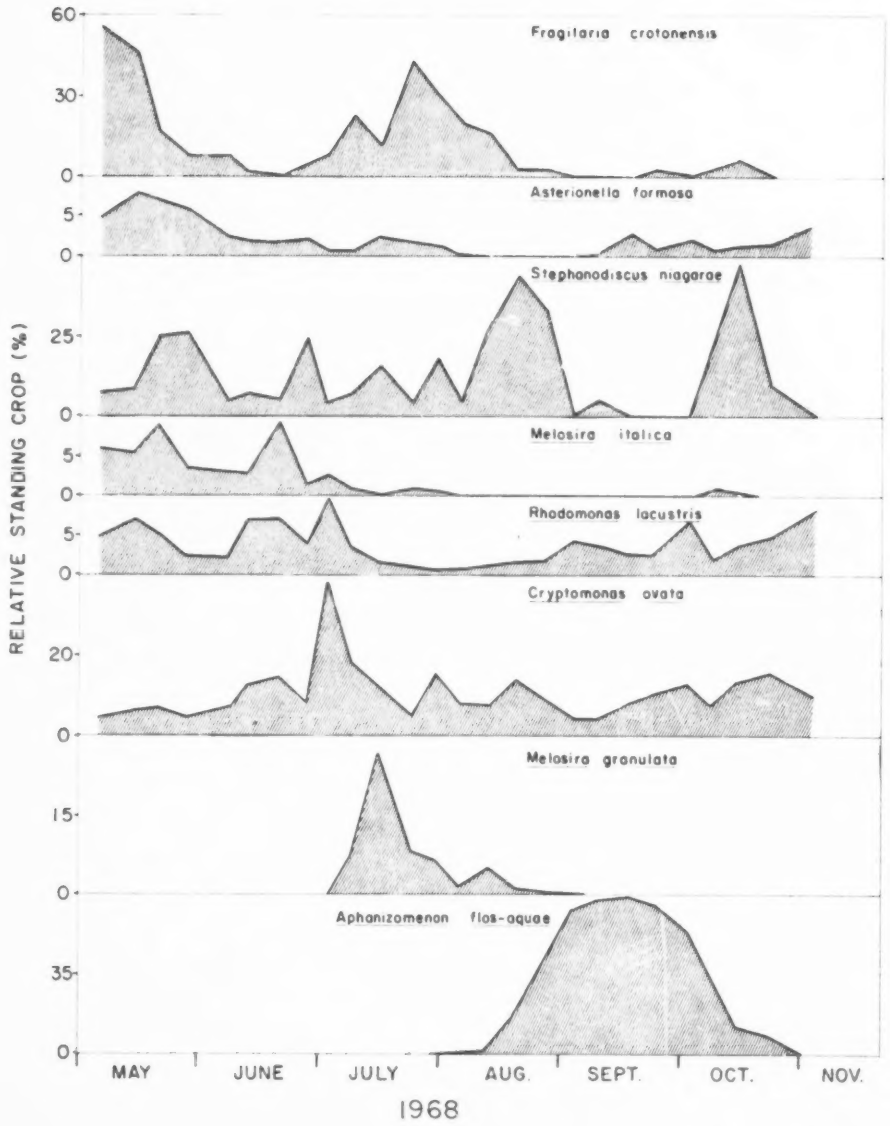

Figure 26. Mean relative standing crop (%) of the eight most abundant phytoplankton species for all sampling stations on Bighorn Lake during 1968.

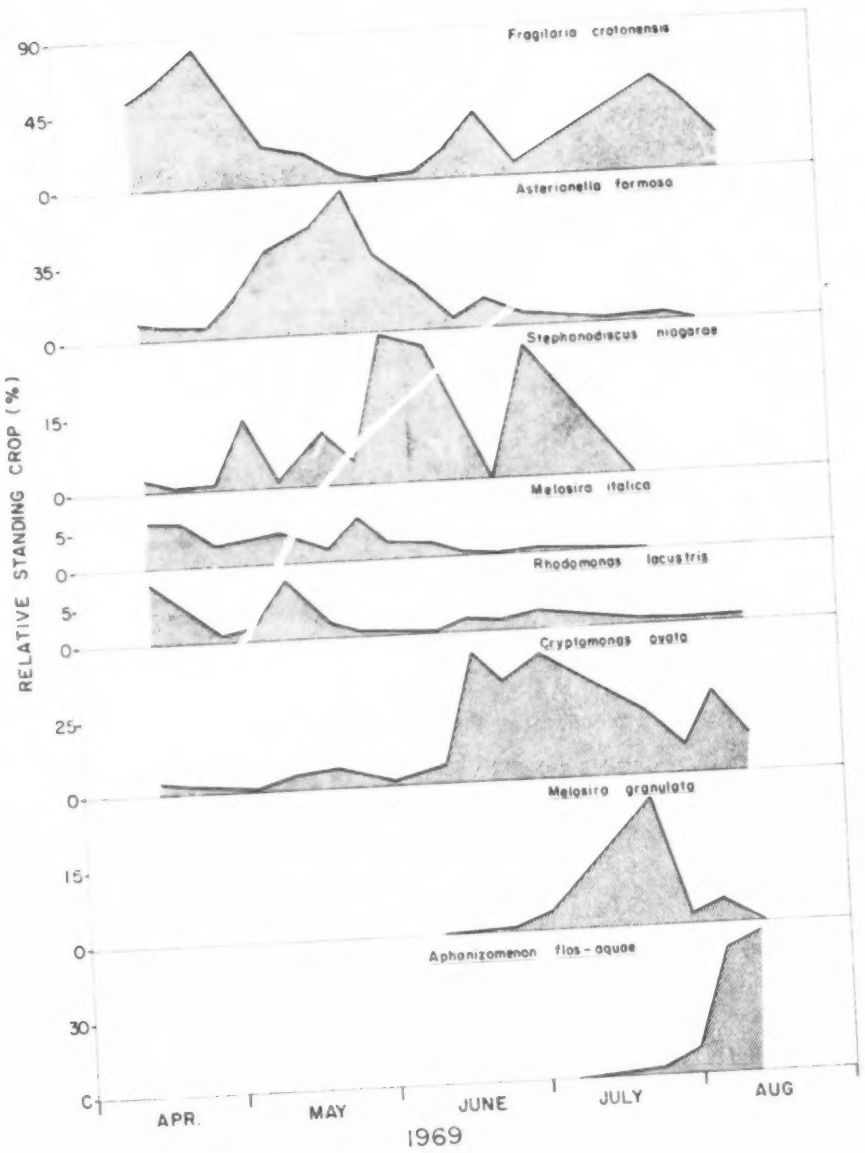

Figure 27. Mean relative standing crop (%) of the eight most abundant phytoplankton species for all sampling stations on Bighorn Lake during 1969.

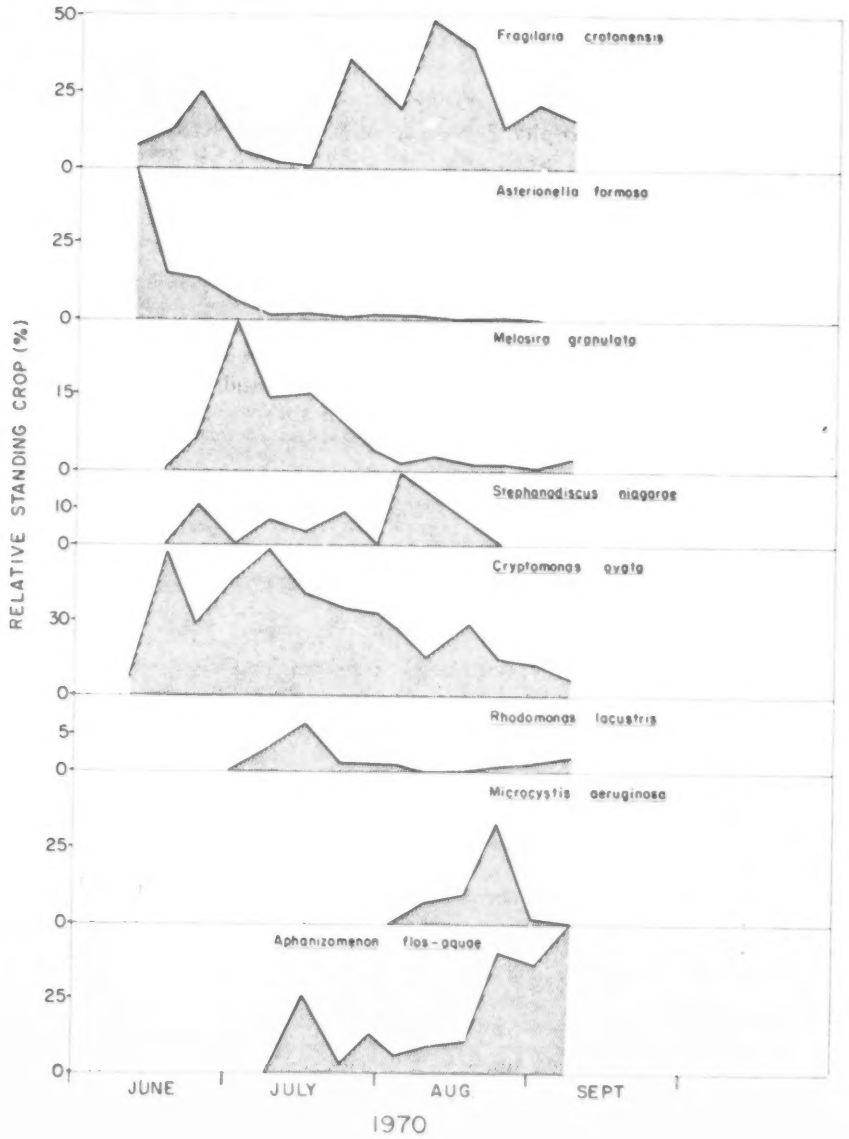

Figure 28. Mean relative standing crop (%) of the eight most abundant phytoplankton species for all sampling stations on Bighorn Lake during 1970.

5 to station 0. When standing crop was expressed as the volume under a square meter of reservoir surface to a depth at which light was sufficient for photosynthesis the picture was altered. Table XVIII shows that standing crop increased down-reservoir reaching a maximum at station 3 for 1968 and 1969 and station 2 for 1970.

A similar pattern was observed with chlorophyll a concentrations (Table XVIII). Chlorophyll a (mg/m^2) increased down-reservoir and attained a maximum at station 2 for 1968 and 1969, and station 3 for 1970.

Chlorophyll a concentrations (mg/m^3) in the euphotic zone during the study are given in Table LXVI of Appendix C. These values represent the mean chlorophyll a concentration of the profile taken through the euphotic zone assuming a homogeneous vertical distribution of phytoplankton. In general, chlorophyll concentrations (mg/m^3) were highest at the upper end of the reservoir and decreased downstream to station 0. Mean daily chlorophyll a concentration was 8.3 mg/m^3 in 1968 and 1969, and 10.1 mg/m^3 in 1970, or 21.6% greater in 1970.

The maximum concentration of chlorophyll a was 77.0 mg/m^3 on 9 September 1968, 39.7 mg/m^3 on 4 August 1969 and 34.5 mg/m^3 on 29 July 1970, and occurred during a period of large standing crops of Aphanizomenon for 1968 and 1969.

Figure 29 presents the relationship between average chlorophyll a concentrations and total cell volumes in the euphotic zone during the study. Chlorophyll a concentrations followed phytoplankton volumes and the correlation coefficients were $r = 0.28$ ($P = 0.01$) for 1968, $r = 0.37$ ($P = 0.01$) for 1969, $r = 0.12$ ($P => 0.05$) for 1970 and $r = 0.27$ ($P = 0.01$) for all years taken together.

The regression equation using mean chlorophyll a concentrations and total standing crops at each station for each year was calculated:

$$\text{Chlorophyll } (mg/m^3) = 0.97V + 3.47 \qquad R^2 = 28\%$$

where V equals the mean phytoplankton standing crop (mm^3/l). The equation indicates that the relationship between chlorophyll and cell volume was non-linear.

The histograms portrayed in Figure 30 show the frequency at which certain ratios of chlorophyll a and total cell volume occurred during the sampling periods for the indicated year. Over 57% in 1968, 88% in 1969 and 69% in 1970 of the ratios occurred within the interval 0-4 µg chlorophyll a/mm^3 of cells. The mean ratios, medians and modes of µg chlorophyll a/mm^3 of cells are given in Figure 30. On the basis of the presented data, the average relationship between chlorophyll a

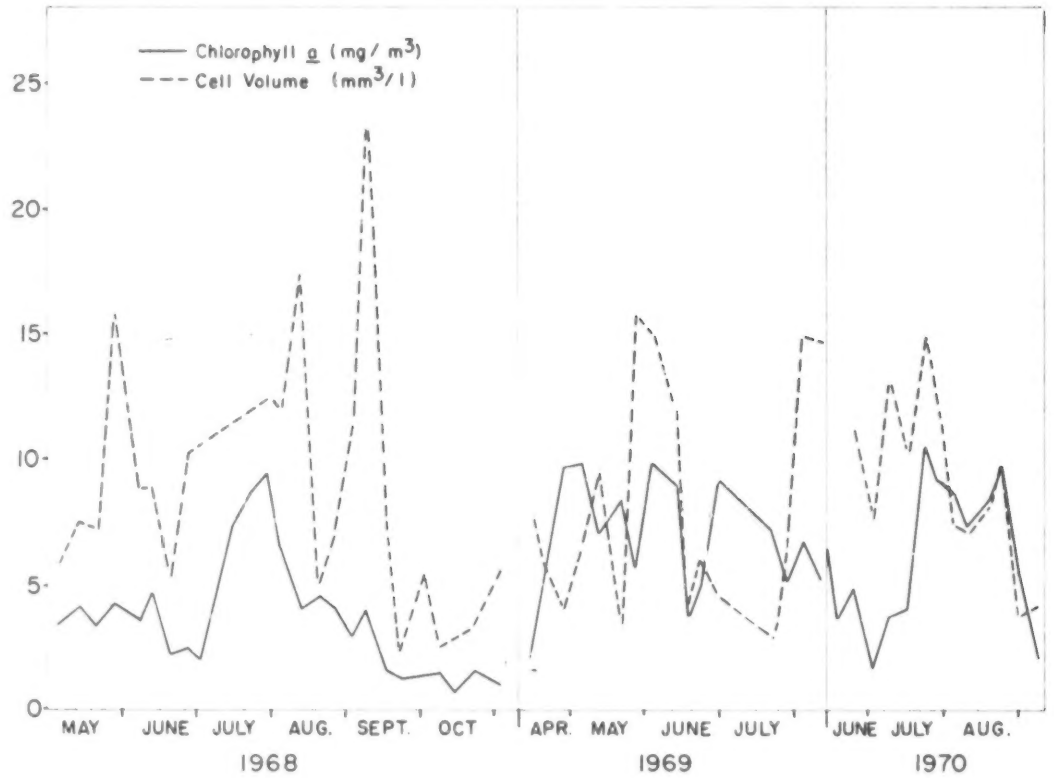

Figure 29. Relationship between mean total phytoplankton standing crop (mm^3/l) and chlorophyll a concentrations (mg/m^3) for all stations during the study, Bighorn Lake.

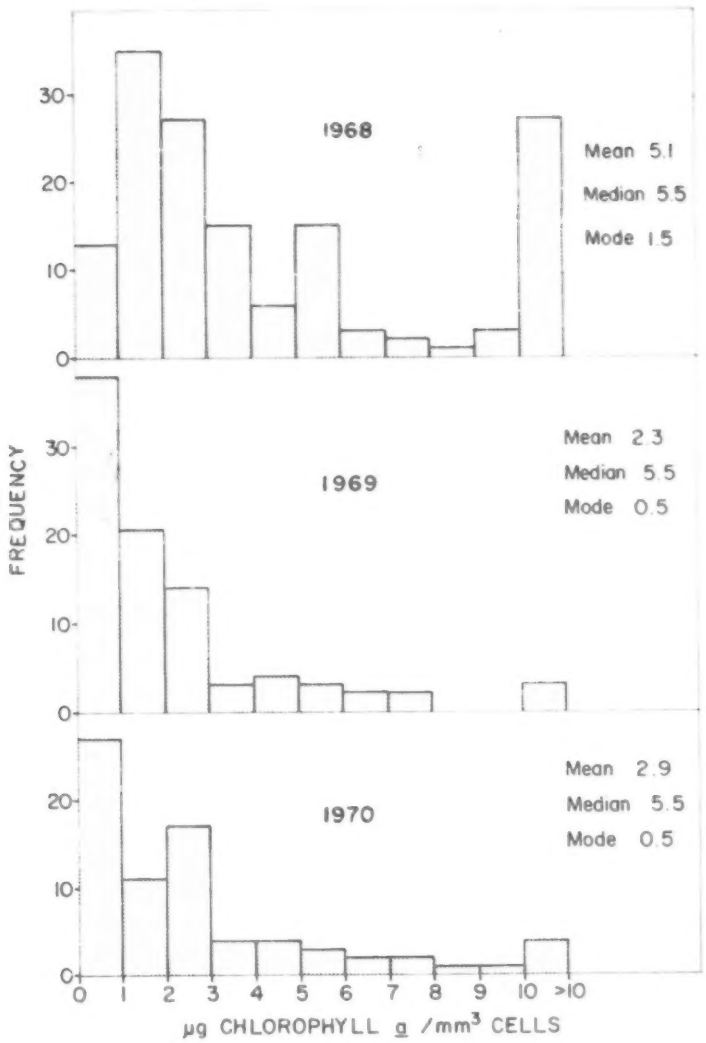

Figure 30. Frequency of the ratios of chlorophyll a to cell volume ($\mu g/mm^3$) during the study, Bighorn Lake.

and cell volume would be 3.4 µg chlorophyll a is equivalent to 1.0 mm^3 of cells. Similar values were obtained by Martin (1967), Peterka and Knutson (1970) and Wright (1959).

Although the average ratio (µg chlorophyll a/mm^3 of phytoplankton) was 3.4, ratios differed somewhat depending upon the season in which the samples were taken (Fig. 31). The ratio of chlorophyll/phytoplankton volume of the samples collected from April to July primarily composed of diatoms, was 3.8. The ratio for the samples taken in July composed primarily of diatoms and flagellates, was 3.1. The ratio of samples taken from August to November when Aphanizomenon was dominant, was 4.5 µg chlorophyll a/mm^3 of cells.

The multiple linear regression equation, utilizing mean euphotic zone data over each year at each station, best explaining the observed variations in the ratio of chlorophyll a to total phytoplankton standing crop during the study is:

Chlorophyll a/total phytoplankton standing crop (µg/mm^3) =

$6.13 - 0.07E + 0.26N + 7.76P - 0.01R \qquad R^2 = 74\%$

where E = euphotic zone depth (m)
N = nitrate nitrogen (mg/l)
P = ortho-phosphate (mg/l)
R = solar radiation (g cal/cm^2)

The most significant variables, in decreasing order of significance, were ortho-phosphate ($r = 0.80$; $P = 0.01$) solar radiation ($r = -0.66$; $P = 0.01$), euphotic zone depth ($r = 0.53$; $P = 0.05$) and nitrate nitrogen ($r = 0.48$; $P = 0.05$).

Primary Productivity

Accurate daily photosynthesis predictions based on environmental factors cannot be made because of the unpredictable fluctuations in these factors from day to day. However, averaging of these factors over longer periods of time reduces fluctuations and permits their use in calculating photosynthesis.

The method of Ryther and Yentsch (1957) uses the equation:

$$P = \frac{R}{k} \times C \times 3.7 \qquad (1)$$

where P is the productivity in grams carbon per square meter per day, R is a variable, relative rate of photosynthesis-- the value of which is fixed by the amount of solar radiation, k is the extinction coefficient of the water column, C is the average chlorophyll concentration and 3.7 is an average assimilation ratio at light saturation--

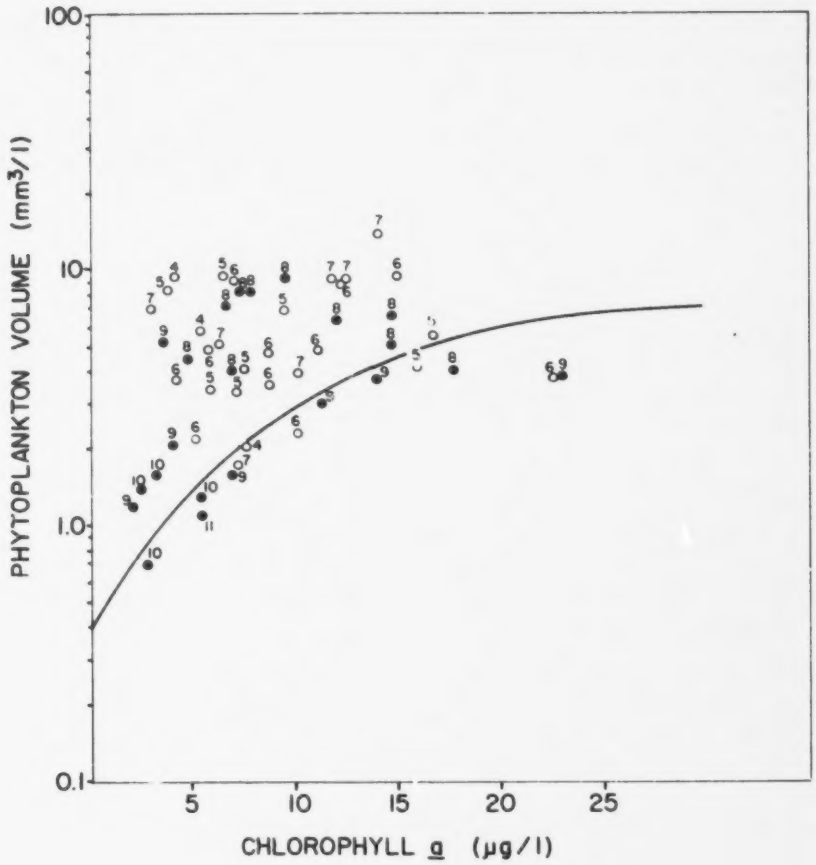

Figure 31. Seasonal relationship between mean chlorophyll a concentration (µg/l) and algal cell volume (mm^3/l) for all stations during the Bighorn Lake study. Open circles represent samples which contained virtually no blue-green algae while closed circles represent samples which contained predominately blue-green algae. The solid line represents a 3.42:1.00 ratio of chlorophyll a to phytoplankton volume. Month of sample is shown by the number near the circle.

the units of which are grams carbon per gram chlorophyll per hour. The weakest point of this method was the fixed average assimilation ratio of 3.7.

Curl and Small (1965) obtained better comparisons between the chlorophyll-light method and C^{14} measured values by using a locally obtained ratio.

Wright (1959) replaced the constant in equation (1) with variables characterizing the local situation. The resultant equation was:

$$P = \frac{4.6}{k} \times F \times T \times C \times R_{opt} \qquad (2)$$

where 4.6/k sets the lower limit of the euphotic zone, F is the ratio of photosynthesis at light saturation to total euphotic zone photosynthesis, T is the number of hours of photosynthesis, C is chlorophyll concentration and R_{opt} is the assimilation ratio at light saturation.

Martin (1967) demonstrated that over a wide range of light conditions the assimilation ratio at light saturation is independent of the amount of sunlight falling on the water surface. There was also the relationship between the assimilation ratios obtained by both gross O_2 and C^{14} fixation measurements, and average temperature of the euphotic zone.

Utilizing the observed relationship between temperature and assimilation ratios, Martin modified equation (1) as follows:

$$P = \frac{R}{k} \times C \times A_t \qquad (3)$$

where all variables are the same as in equation (1) and A_t is the temperature dependent assimilation ratio.

Peterka and Reid (1968) made an attempt to show the influence of various environmental factors that significantly influenced photosynthetic rates in Lake Ashtabula, North Dakota. A multiple linear regression analysis of their data revealed that chlorophyll, water temperature and Secchi disk transparency were the only significant variables affecting photosynthesis. Chlorophyll and water temperature together explained 65% of the variation in photosynthesis.

The methods of Wright (1959) and Martin (1967) appear to be approaches in the right direction. Wright's method takes into account seasonal variation in the vertical productivity profiles and Martin's method utilizes a variable assimilation ratio based on knowledge of the euphotic zone temperature.

Mean values of net primary productivity (calculated by using Martin's method of prediction) at each station and seasonal fluctuations of primary production during the study are presented in Figure 32. A photosynthetic quotient (PQ) of unity was assumed in converting carbon measurements into units of oxygen. Ryther (1956a) and Strickland (1960) have reviewed a number of experiments designed to determine PQ of various planktonic algae and found values ranging from less than unity to 1.6 or greater in a nitrate containing medium.

Average daily primary production was 0.51 g C/m^2/day (1.36 g O_2), 0.55 g C/m^2/day (1.46 g O_2) and 1.42 g C/m^2/day (3.78 g O_2) for 1968, 1969 and 1970, respectively. Maximum production occurred on 29 July 1970, 6.96 g C/m^2/day (18.51 g O_2).

An attempt was made to determine how much of the variation in the predicted production rates was accounted for by the various parameters used in the calculations. A multiple linear regression equation was calculated using the means of all data at each station for each year. The equation expressing the relationship is:

$$\text{Primary Productivity (g } C/m^2\text{/day)} = -3.8 - 0.04E + 0.02C + 0.01R + 0.14T \qquad R^2 = 90\% \quad (4)$$

where E = mean extinction coefficient of the euphotic zone (k/m)
C = mean chlorophyll concentration of the euphotic zone (mg/m^3)
R = solar radiation incident to the reservoir surface (g cal/cm^2)
T = mean temperature of euphotic zone (C)

The above equation (4) demonstrates that the linear regression equation accounted for most of the observed variation in the mean production rates calculated using a non-linear combination of independent variables, equation (3).

In the future, it would be desirable to make actual primary production estimates (preferably using C^{14}) and sample the euphotic zone for the parameters needed to predict primary production. A complete multiple correlation and regression analysis of the collected data would not only reveal the degree of similarity between estimates, but would strengthen (or possibly weaken) the assumptions made in the many models of predicting primary productivity.

Many authors (Manning and Juday, 1941; Edmondson, 1955; Ryther, 1956b) have observed a rather constant relationship between chlorophyll *a* and photosynthesis. By using the mean euphotic zone data at each station for each year, it was found that chlorophyll *a* (mg/m^2) accounted for 67% of the calculated variation in primary productivity, while phytoplankton standing crop ($X10^3 mm^3/m^2$) only accounted for 21% of the observed variation in the calculated production rates during the study.

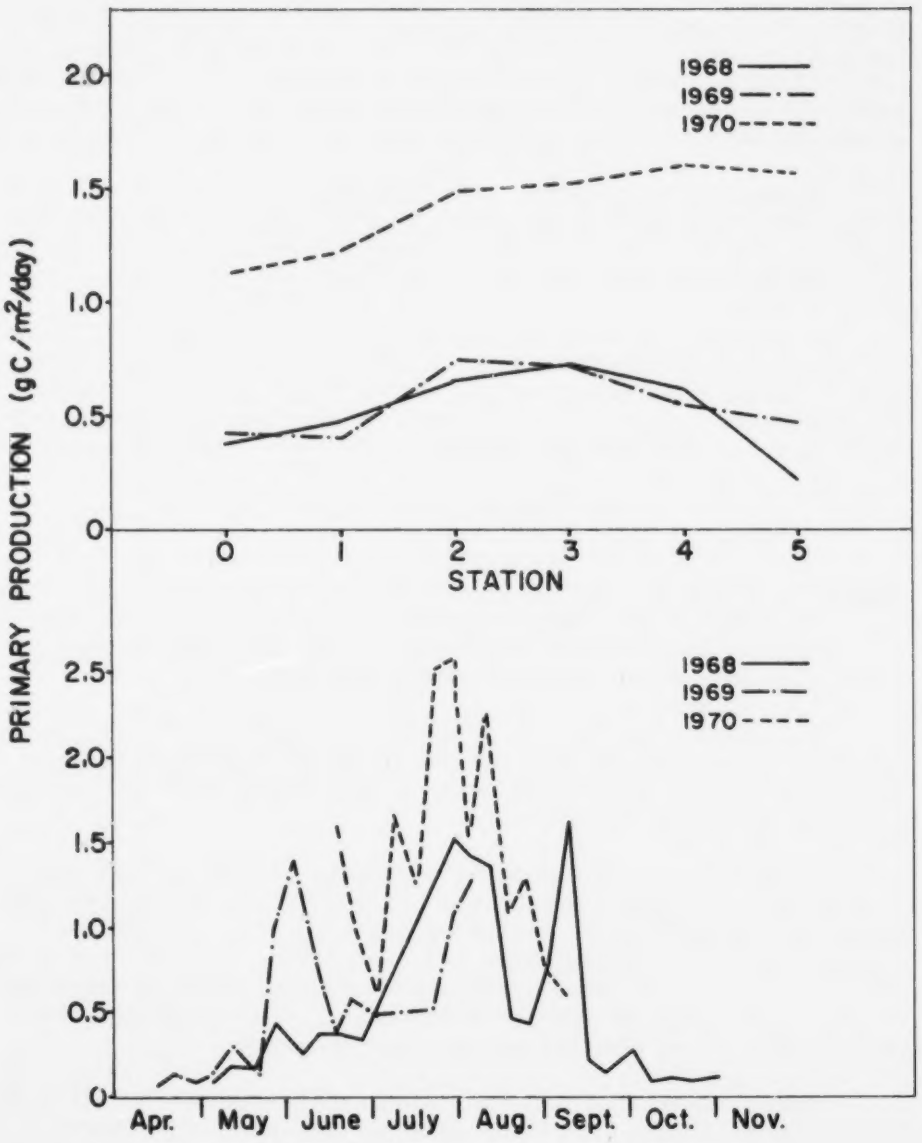

Figure 32. Mean primary productivity (g C/m^2/day) at each station and seasonal fluctuations of primary production during the study, Bighorn Lake.

Relationships of Physical and Chemical Parameters to Chlorophyll and Total Phytoplankton Standing Crop

Multiple linear regression analysis was used to predict standing crops of chlorophyll a and phytoplankton using 14 independent variables (Table XIX). Chlorophyll a and total phytoplankton standing crop were not used as independent variables, because they are strongly interrelated. The various multiple regression equations were calculated using mean euphotic zone data over each year at each station.

The equation best expressing the observed variation in chlorophyll a on an areal basis during the study is:

$$\text{Chlorophyll } a \text{ } (mg/m^2) = 24.26 - 95.62N + 1.66T + 0.28K \qquad R^2 = 65\% \qquad (5)$$

where N = nitrate nitrogen (mg/l)
T = temperature (C)
K = conductivity (micromhos)

The most significant variables, in decreasing order of significance, were nitrate nitrogen ($r = -0.74$; $P = 0.01$), conductivity ($r = -0.67$; $P = 0.01$) and temperature ($r = 0.58$; $P = 0.05$). Therefore, it can be shown that 44% (0.67 X 0.65) of the observed variation in the calculated mean primary productivity can be accounted for by the above environmental variables.

The equation best expressing the variations observed for phytoplankton standing crop on an areal basis is:

$$\text{Total phytoplankton standing crop } (X10^3\ mm^3/m^2) = -34.24 - 80.54N - 4.30P + 0.23R + 0.03K \qquad R^2 = 65\% \qquad (6)$$

where N = nitrate nitrogen (mg/l)
P = ortho-phosphate (mg/l)
R = solar radiation (g cal/cm^2)
K = conductivity (micromhos)

The most significant variables, in decreasing order of significance, were nitrate nitrogen ($r = -0.67$; $P = 0.01$), solar radiation ($r = 0.60$; $P = 0.01$), ortho-phosphate ($r = 0.57$; $P = 0.05$) and conductivity ($r = -0.43$; $P = 0.05$). Phytoplankton standing crop and the above environmental factors would only account for 14% (0.21 X 0.65) of variation in the calculated mean primary productivity.

Variations in chlorophyll a (mg/m^3) observed during the course of the study are best expressed by the following equation:

Table XIX. Variables used for multiple linear regression analysis of chlorophyll a and total phytoplankton standing crops for 1968, 1969 and 1970, Bighorn Lake.

Dependent variables:

1. Chlorophyll a (mg/m^3)
2. Chlorophyll a (mg/m^2)
3. Total phytoplankton standing crop (mm^3/l)
4. Total phytoplankton standing crop ($X10^3$ mm^3/m^2)

Independent variables:

1. Euphotic zone depth (m)
2. Extinction coefficient (k/m)
3. Nitrate nitrogen (mg/l NO_3^--N)
4. Nitrite nitrogen (mg/l NO_2^--N)
5. Ammonia nitrogen (mg/l NH_3-N)
6. Total inorganic nitrogen (mg/l N)
7. Ortho-phosphate (mg/l $PO_4^{\equiv}$)
8. Ortho-phosphate to nitrate nitrogen ratio
9. Total iron (mg/l)
10. Manganese (mg/l Mn^{++})
11. Copper (mg/l Cu^{++})
12. Zinc (mg/l Zn^{++})
13. Temperature (C)
14. Conductivity (micromhos)

chlorophyll *a* (mg/m^3) =
$13.03 - 1.38\bar{E} - 2.48N + 9.56P + 0.23T \quad R^2 = 93\% \quad (7)$

where E = euphotic zone depth (m)
N = nitrate nitrogen (mg/l)
P = ortho-phosphate (mg/l)
T = temperature (C)

The most significant variables, in decreasing order of significance, were euphotic zone depth ($r = -0.94$; $P = 0.01$), ortho-phosphate ($r = 0.59$; $P = 0.01$), nitrate nitrogen ($r = 0.38$; $P = > 0.05$) and temperature ($r = 0.32$; $P = > 0.05$).

The equation best explaining the observed variations in phytoplankton standing crop on a volume basis during the study is:

Total phytoplankton standing crop (mm^3/l) =
$-16.10 - 0.52E - 2.65N + 0.06R \quad R^2 = 76\% \quad (8)$

where E = euphotic zone depth (m)
N = ammonia nitrogen (mg/l)
R = solar radiation (g cal/cm^2)

The most significant variables, in decreasing order of significance, were solar radiation ($r = 0.63$; $P = 0.01$), euphotic zone depth ($r = -0.57$; $P = 0.05$) and ammonia nitrogen ($r = 0.34$; $P = 0.05$).

Equations (7) and (8) point out that light appears to be the major variable controlling the density of organisms. It is also apparent by comparing equations (5) and (6) with (7) and (8) that the measured independent variables are much more efficient predictors on a volume basis than on an areal basis.

DISCUSSION

The chemical budget of the major ions (Table VIII) demonstrated that there was a slight decrease in the total dissolved solids (salinity) as the water moved down-reservoir. Hence, the reservoir was acting as a salinity trap. Because of the extensive development of irrigation projects and reuse of water along a series of impoundments, salinity often poses a major pollution problem.

Neel, (1963) found with the impoundment of the Missouri River by Fort Randall Dam, the water quality of the reservoir was considerably altered by carbonate precipitation, resulting in the increased ratio of sodium to calcium. In Bighorn Lake, the above ratio was essentially the same for the weighted average of the influent streams versus that of the reservoir discharge for both 1968 and 1969. Since these ratios were of the same magnitude, it was concluded that biogenic precipitation of calcium was not evident.

The entrance of flood waters into reservoirs created currents which vary in magnitude due to the physical and chemical parameters found in the reservoir (Wiebe, 1938, 1939, 1940, 1941; Lyman, 1944; Anderson and Pritchard, 1951). The 1968 Bighorn Lake data reveal that a turbidity current was established in the reservoir due to subsurface withdrawal through the power penstocks (Fig. 19). The development of the current was attributed to the excessive withdrawal of water from the reservoir during 1968 and was thought to extend most of the length of the reservoir. This current was not detectable during the 1969 and 1970 sampling periods.

A tongue of ortho-phosphate (Fig. 20) and nitrate nitrogen (Fig. 21) rich water, which was associated with the turbidity current, developed in Bighorn Lake at station 0 during the summer and early fall of 1968 at the elevation of the power penstock. The discharge of such nutrient rich water should have had a marked influence on downstream production (downstream eutrophication). Neel (1963) discusses several cases of greatly increased downstream production following impoundment.

Also at the depth of the power penstock during 1968, a layer of water with minimum oxygen content (Fig. 22) and pH (Fig. 23) developed. Kittrell (1959) cites several cases in which effluents of low oxygen content from dams have resulted in problems (i.e., oxygen concentrations are low enough that downstream biochemical oxygen demand cannot be met).

Deep water withdrawal in a reservoir tends to deplete the reservoir system of nutrients since the effluent will be carrying

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away the nutrients that would otherwise tend to accumulate in the deep water of a natural lake during summer stagnation (Ruttner, 1963). However, for Bighorn Lake it has been shown that some of the nutrients that entered the reservoir were retained (Table IX). Of the total nitrogen that entered the system, 75% was discharged. The largest inorganic nitrogen loss was in ammonia, while an 11% increase of nitrate nitrogen occurred. Only 14% of the total phosphorus that entered the reservoir was discharged from it. A 32% decrease in ortho-phosphate was observed.

It was apparent that when streamflows were high for the Bighorn and Shoshone Rivers, the reservoir was fertilized with the nutrients associated with the suspended sediments.

Important nutrients in many natural waters are often limiting to phytoplankton production (Hutchinson, 1957; Fogg, 1965; Lund et al., 1963). Various workers have discussed the concentrations of nitrogen and phosphorus that are needed for an algal bloom. The National Technical Advisory Committee on Water Quality (Anon., 1968) suggests that a concentration of at least 0.015 mg/l of phosphorus is necessary for algal growth. Hutchinson (1957) states that Asterionella can take up phosphorus where it is present at less than 0.001 mg/l. Mackenthun (1965) showed that nuisance blooms of algae may be expected when inorganic phosphate and nitrogen reach average concentrations exceeding 0.01 mg/l and 0.30 mg/l, respectively. Wright (unpublished data) found from his studies on Canyon Ferry Reservoir, Montana, that a large increase in phosphate resulted in a strikingly large increase in blue-green populations. The above levels for nitrogen and phosphate were usually exceeded at all stations of Bighorn Lake and were not considered limiting to algal growth.

Wright (1960) suggested carbon dioxide to be limiting in reservoirs during dense phytoplankton blooms. Talling (1960b) found little reduction of the nutrient in relation to natural rates of photosynthesis. Lewin (1962) discusses various other elements (e.g., iron, manganese, etc.) and their importance to phytoplankton productivity. In general, the concentration of these nutrients in Bighorn Lake are high enough to be considered non-limiting.

The steady depletion of nutrients from the epilimnion during the summer leaves two alternatives of replenishment of nutrients for continued algal growth: (1) nutrients must be added from external sources or (2) the nutrients present must be rapidly recycled.

There was an ortho-phosphate depletion of the surface waters of the reservoir from May to August during the 1968 sampling periods at station 0 (Fig. 20). This loss of phosphate was attributed to uptake by phytoplankton. Slightly increased concentrations of

phosphate in the surface waters during August and September were associated with low conductive water that originated from the high flow conditions in June. The levels of phosphate observed during the period of depletion were still above the minimal levels described by the literature to be limiting.

Epilimnetic phosphate regeneration has also been shown to be mediated by zooplankton. Barlow and Bishop (1965) showed that Daphnia liberated about 80% of the assimilated phosphorus back into the epilimnion during a period of strong stratification. Environmental conditions (e.g., temperature) would affect the rate of such a recycling process. Pomeroy et al. (1963) found turnover times for total phosphorus as low as eight days.

In contrast to ortho-phosphate there was no decline in nitrate nitrogen in the euphotic zone (Fig. 21); instead, concentrations increased during September and October of 1968, which corresponds to a period of maximum development of blue-greens.

Dugdale and Dugdale (1962) have stressed the importance of nitrogen fixation in the overall nitrogen metabolism of freshwaters. Most workers agree that species of Anabaena are the principle nitrogen fixers in the phytoplankton community. However, other authors (Krauss, 1958, Sawyer and Ferullo, 1961) have reported fixation of nitrogen by Aphanizomenon, which comprised the largest standing crop of the blue-green group in Bighorn Lake.

Ryther (1956b) and Edmondson (1956) have both stressed the importance of sunlight as a limiting factor to phytoplankton production. The direct effect of light as it penetrates the water is to increase the standing crop of phytoplankton assuming other environmental factors are not limiting.

Chlorophyll a (mg/m^3) and total phytoplankton standing crops (mm^3/l) for Bighorn Lake decreased from stations 5 to 0. However, reference to Figure 13 shows that water clarity increased downreservoir as the result of the settling out of silt. Therefore the effective depths at which photosynthesis could occur increased downreservoir. The picture is altered when account is taken of this factor, and chlorophyll a and phytoplankton standing crop are expressed as the concentrations and volumes under a square meter of reservoir surface to a depth at which light is sufficient for photosynthesis. Table XVIII shows if chlorophyll a (mg/m^2) and phytoplankton standing crops ($X10^3$ mm^3/m^2) are expressed on an areal basis, then the two measures of the phytoplankton community increased downreservoir and attained maximums between stations 1 and 3. More effective light penetration is obviously important to the explanation of this situation. The lower chlorophyll a (mg/m^2) and phytoplankton

standing crops ($X10^3 mm^3/m^2$) at stations 1 and 0 for 1968 and 1969, and station 0 for 1970 cannot be explained in this manner since the water was more transparent (Fig. 14).

When nutrient conditions for all three years are compared with the euphotic zone chlorophyll a concentrations (mg/m^2), it will be noted that total inorganic nitrogen and ortho-phosphate concentrations (Table XIV) are greatest at the upper end of the reservoir, but no significant difference was found between stations 2, 1 or 0 to explain the decrease in chlorophyll a (mg/m^2) at the latter two stations.

Zooplankton densities must be considered as an important influence on phytoplankton standing crops and thus chlorophyll a concentrations, and may be the factor responsible for the lower phytoplankton production at stations 1 and 0. Wright (1954, 1958, 1965) and many other workers (Anderson et al., 1955; Comita and Anderson, 1959; Edmondson et al., 1962; Richman, 1966) have found declines in phytoplankton standing crops due to heavy predation by zooplankton. However, Edmondson (1962, 1965) demonstrated that zooplankton preferred the microplankton portion of the standing crop. Tappa (1965) has shown that Daphnia exhibits a degree of food selectivity.

It is quite possible that organisms such as Cryptomonas, Rhodomonas and other microplankton would be heavily grazed as food species in Bighorn Lake. The food value of such organisms as Aphanizomenon which comprise the bulk of the phytoplankton standing crop in late summer and early fall, is questionable. Knutson (1970) showed that Daphnia numbers were high during almost unialgal blooms of Aphanizomenon and concluded that Daphnia were grazing upon this blue-green alga. He also pointed out that the frequent periods of large rotting stands of Aphanizomenon would invite the growth of protozoans and bacteria which could serve as food.

Blue-green algae are often the dominant algae in eutrophic lakes, probably because they are free from grazing by zooplankters (Lund, 1969). Aphanizomenon comprised about 70% of the total phytoplankton volume during the late summer and early fall in Bighorn Lake. Large stands of this blue-green have been recorded for other eutrophic lakes (Hammer, 1964; Hrbaeck, 1964; Martin, 1967; Olive et al., 1969).

As the concentration of algal cells increases, light penetration decreases, so that the phytoplankters become self-shading. Inverse correlations between plankton density and light penetration have been described (Fogg, 1965; Javornicky, 1966), but in the field it is usually difficult to establish the direct causal relationships due to unknown effects of detritus and other non-algal forms of turbidity. Talling(1960a) however, has reported a case of self-shading in a field study of an Asterionella population. The appearance of Aphanizomenon in Bighorn Lake may have limited the growth of other algae,

particularly Melosira granulata, Fragilaria crotonensis and Stephanodiscus niagarae (Figs. 26, 27 and 28) due to its characteristic waterbloom and resulting shading effect (Verduin, 1951).

Temperature is considered to be a causative agent of phytoplankton succession. Different species may predominate at different times because of the interaction between prevailing temperature and other environmental factors. Aphanizomenon development in Bighorn Lake started while water temperatures were about 18 C, with blooms appearing shortly thereafter. Most of the summer blooms occurred at water temperatures of 20 to 25 C, which was close to the temperature range for Aphanizomenon waterblooms in several Canadian Lakes (Hammer, 1964).

Nutrient concentrations not only affect total phytoplankton productivity, but also the species composition of the phytoplankton community. The seasonal succession of phytoplankton cannot be entirely related to the concentration of a single inorganic nutrient nor to any combination of nutrients. However, the occurrence of diatoms usually coincides with higher levels of nutrients present in the spring. The position of the blue-greens in the successional pattern is usually accompanied by low levels of nitrate nitrogen and/or high phosphate to nitrate ratio (Hutchinson, 1967).

The spring phytoplankton peaks were dominated by Fragilaria crotonensis, Asterionella formosa, Melosira italica and Rhodomonas lacustris. The successional pattern for most of the above organisms (Figs. 26, 27 and 28) was similar to what Lund (1965) observed for the succession of algae in Windemere Lake.

Predicted primary productivity values fluctuated greatly from day to day with peak production rates occurring during the summer months. These short time variations of production are perhaps not only the result of daily insolation changes but also the quantity and quality of the phytoplankton standing crop and its horizontal distribution in the reservoir (Rhode, 1958). Bighorn Lake is moderately productive with calculated mean daily net primary productivity values of 1.36 g O_2/m^2/day, 1.46 g O_2/m^2/day and 3.78 g O_2/m^2/day for 1968, 1969 and 1970, respectively. Most of the above productivity rates are low when compared to other eutrophic lakes: 3.0 g O_2/m^2/day in Canyon Ferry Reservoir, Montana (Wright, 1965), 6.9 g O_2/m^2/day during the summer in western Lake Erie (Verduin, 1956). Unproductive waters yielded values less than 0.3 g O_2/m^2/day and the most productive saline and fresh waters may yield 1.3 to 8.0 g O_2/m^2/day (Steeman-Nielsen, 1954; Rhode, 1958). Rhode (1958) arbitrarily considered daily production rates of about 0.3 g O_2/m^2/day as the dividing point between oligotrophic and eutrophic lakes.

The relationship of chlorophyll a concentration to cell volume was shown to be about 3.4 ug chlorophyll a/1.0 mm^3 of algal cells for all data. A range of values derived from the literature is 0.5 (Strickland, 1960) to 7.6 ug chlorophyll a/mm^3 of cells (Cushing, 1958).

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